20680

NATIONAL DEFENSE INDUSTRIAL ASSOCIATION

STRENGTH THROUGH INDUSTRY & TECHNOLOGY

1999 VEHICLE TECHNOLOGIES
ALTERNATIVE PROPULSION SYMPOSIUM

Sponsored By, TACOM-TARDEC

PROCEEDINGS

Event #953
The Ritz-Carlton, Dearborn
Dearborn, Michigan
May 3-5, 1999

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The Army S&T Program ...

and Propulsion for the Army After Next

Dr. A. Michael Andrews II

Deputy Assistant Secretary for Research and Technology

Office of the Assistant Secretary of the Army

Acquisition, Logistics and Technology

Alternative Propulsion Symposium

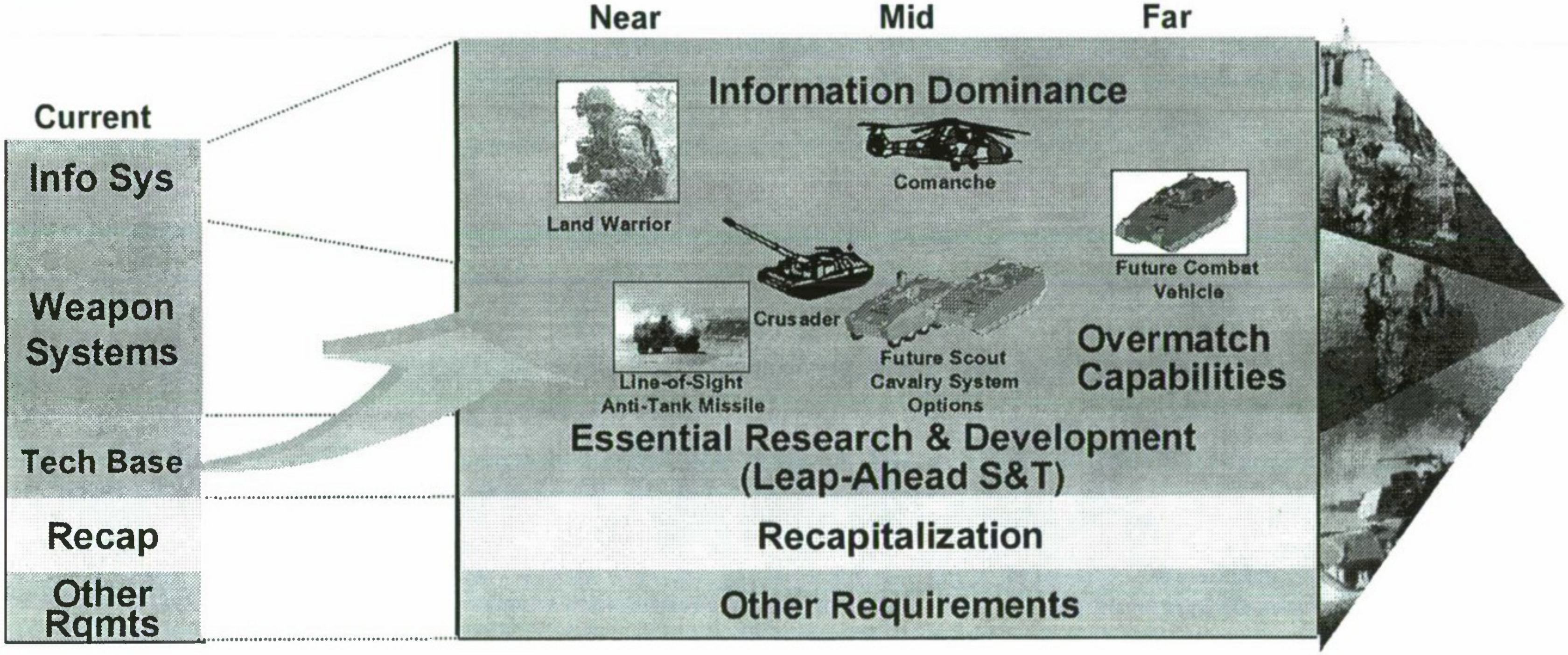
Dearborn, MI

May 4, 1999

Topics

- Army S&T Investment Strategy
- Army S&T Initiatives
- Army Propulsion Investment Strategy
- Future Combat Vehicle (FCV)
- Summary

The Army Investment Strategy



FY 00-05

- Priority on information dominance
- Maintain combat overmatch
- Focus S&T on leap-ahead technology for mid and far terms
  - Indiv warrior power mgmt
  - Wireless communications
  - Fuel efficient propulsion

FY 06-14

- Continue emphasis on information dominance
  - C2 on the move
- Multi-mission UAV payloads
- Active protection systems
- Future Scout Cavalry System
- Lightweight warrior

FY 15-25

Sustain information dominance
Future combat vehicle
Future infantry vehicle
Compact electric power sources
AAN warfighter

Army

After

Next

Army S&T Strategy

FORCE XXI

FY 00-05
- Achieve Proven Innovations

Today's 6.3

FY 06-14
- Bridge to the Next Century

Today's late 6.2 & 6.3

Army XXI

FY 15-25
- A True Revolution in Military Affairs

Today's 6.1 & early 6.2

Army After Next

- **Provide Upgrades to Current Generation Systems**
- **Bridge Fielding Gap Via System Enhancements for Army 2010**
- **Provide Leap-Ahead Capabilities for Army After Next**

Striving to Maintain a Balanced and Dynamic Portfolio for Today...Tomorrow... and the 21st Century

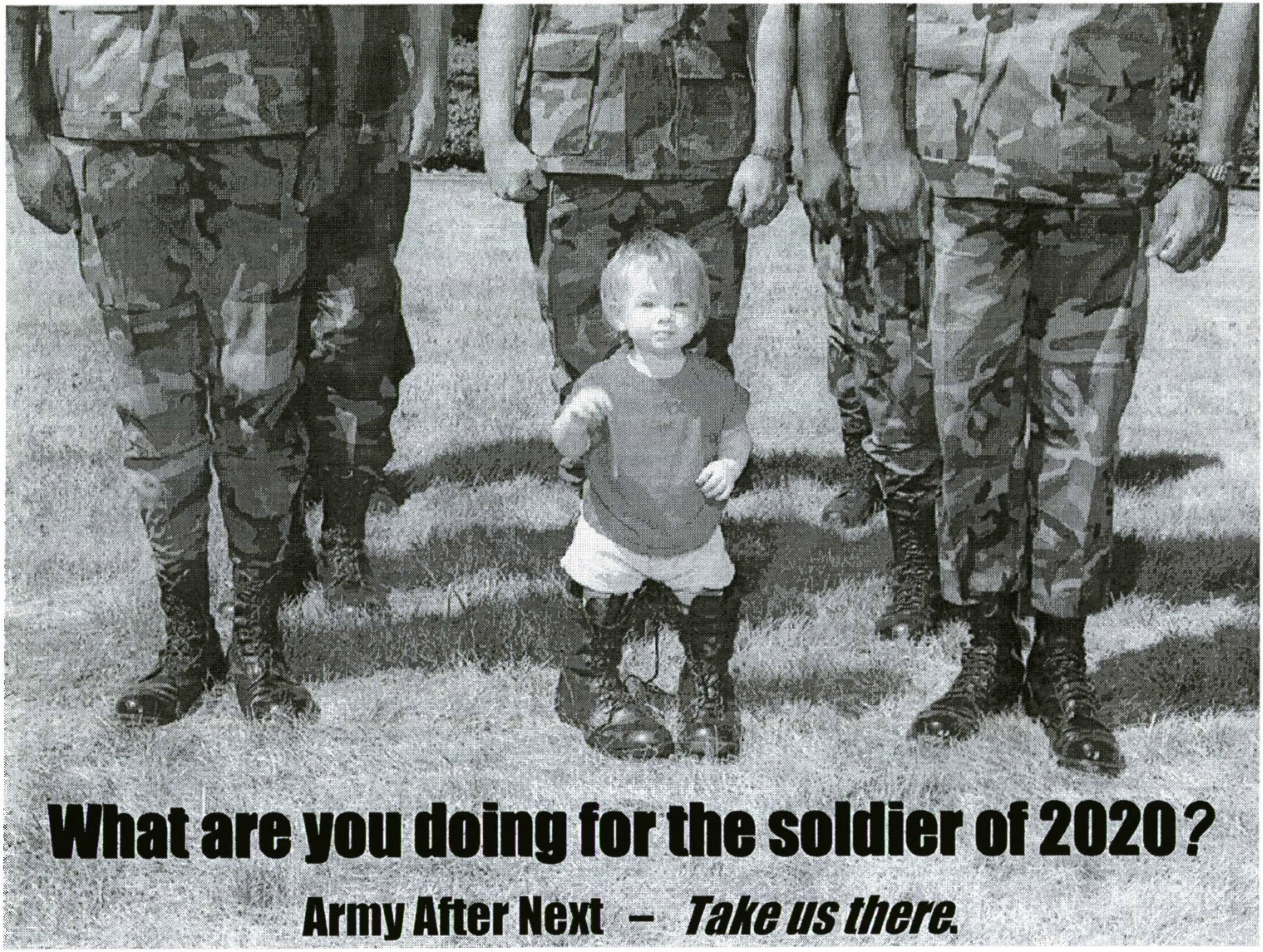
Changing Environment for Technology

- High Expectations for Future Military Capabilities*
  - 3x more effective
  - 3x more mobile
  - 1/3 of today's support
  - Greater dependence on commercial technologies

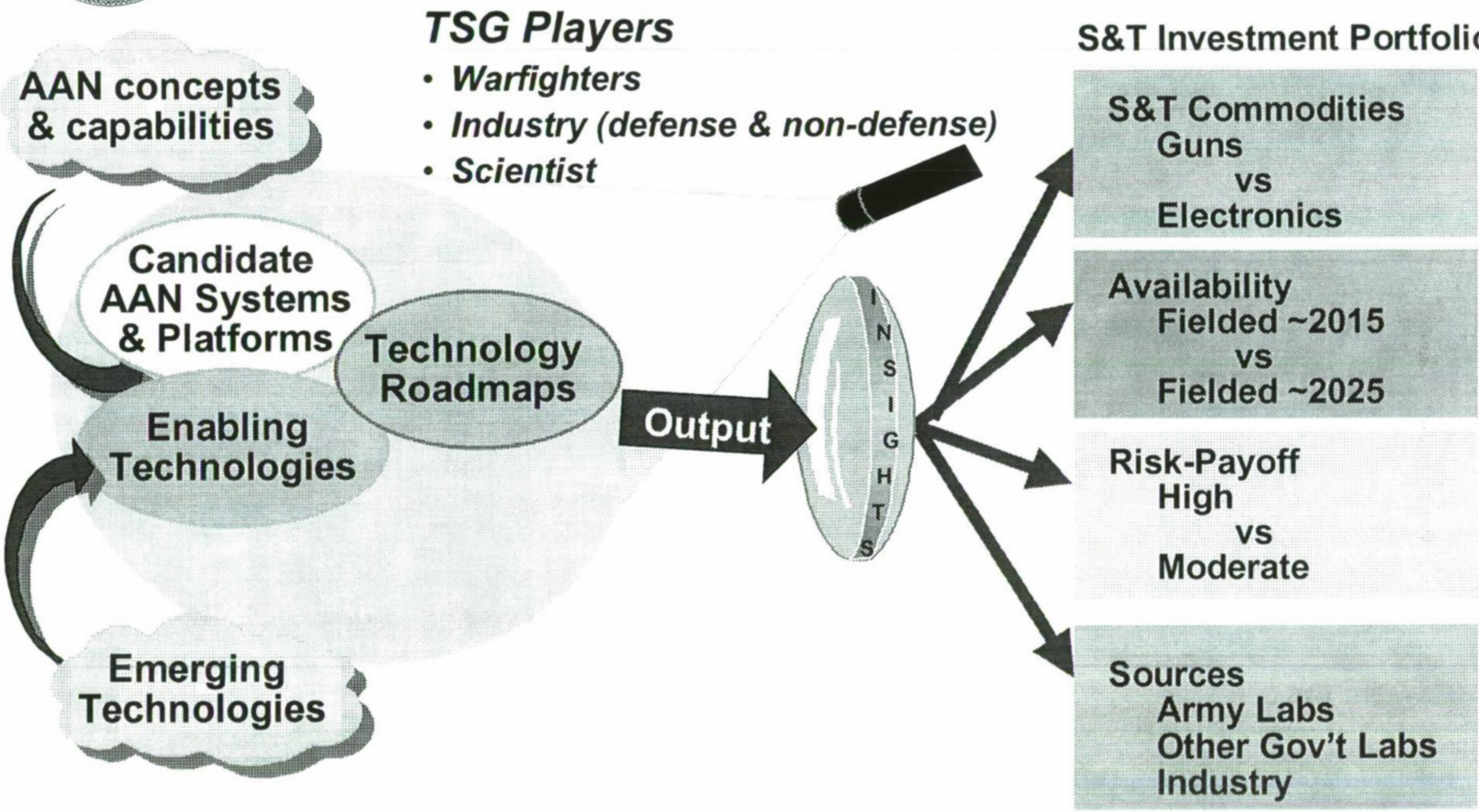
- AAN Contingency Forces- enabled by leap-ahead technologies
  - Rapidly deployable
  - Lethal forces
  - Conduct combat operations for limited periods without resupply
  - Survivable
  - Versatile - able to fight/deploy in various environments

- Greater Reach Expected for Military Technology Investments
  - Accelerated cycle Times
  - Quantum improvements in products between cycles
  - Global phenomenon - worldwide marketplace

* ASB Summer Study Briefing, October 1998


What are you doing for the soldier of 2020?
Army After Next – *Take us there.*

Technology Seminar Game

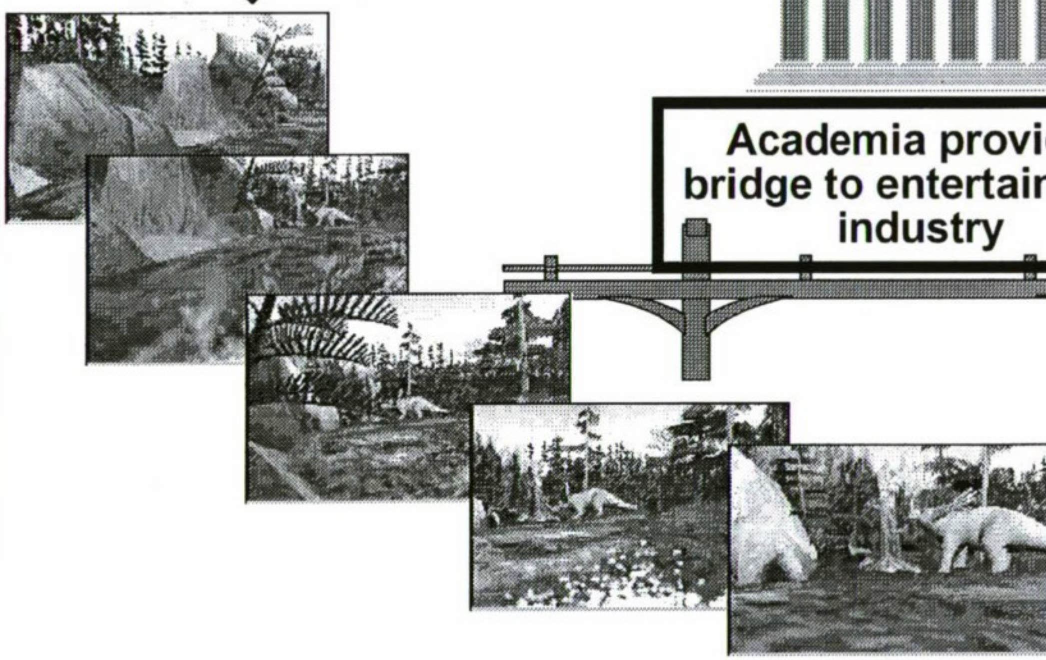


Objective: Provide insights to shape S&T investment strategy to enable warfighter concepts required by AAN era forces

Modeling & Simulation…
Linking Entertainment and Defense

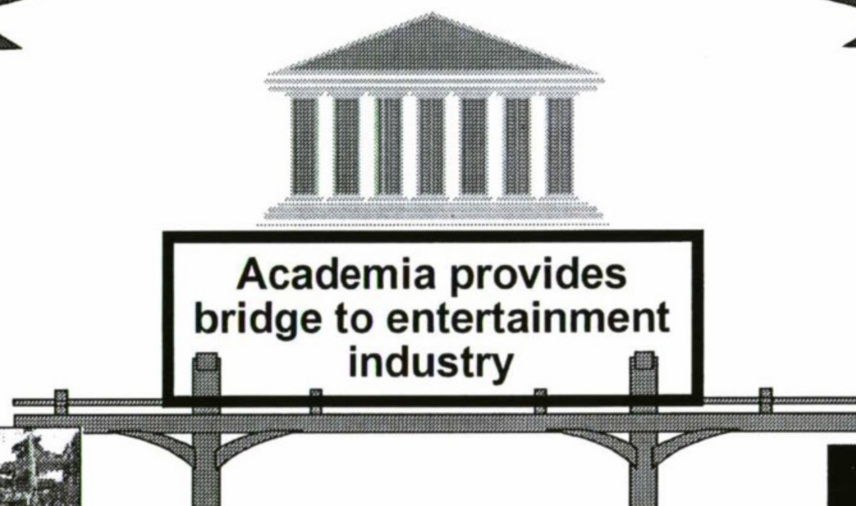
Partnership with academia and entertainment industry to leverage innovative research and concepts for training and design

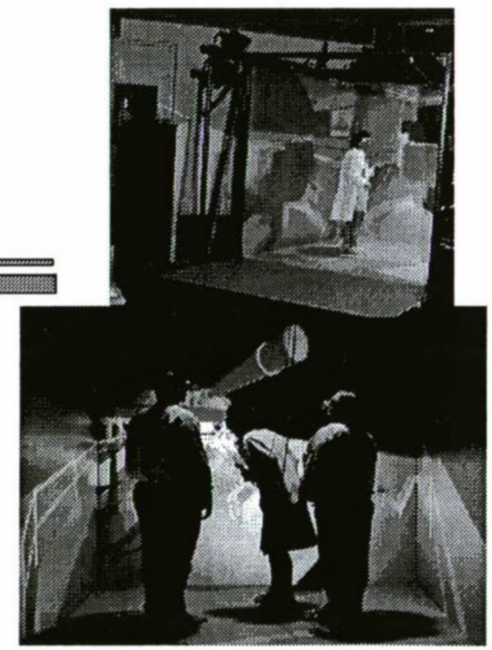
Leverage entertainment/ electronic game industry



Academia provides bridge to entertainment industry

Apply "imagineering" to warfighter training





Responding to 1997 National Research Council Report

Army S&T Propulsion Investment Strategy

- Leverage commercial investments/products
  - Modify commercial engines for military use ... no new military unique engines on the horizon
  - Use National Automotive Center (NAC) as catalyst and focal point for Army/industry/academia collaboration
- Focus on new platform applications (i.e., FCV)
  - Emphasis on revolutionary versus evolutionary
  - Increase investments in innovative technology (e.g, fuel cells & reformers) -- NAC
- Seek partnerships with Other Government Agencies (e.g., DARPA, DOE)
  - Combat Hybrid Power System (CHPS)
  - Electric Drive
  - 21st Century Truck (dependent on non-DoD $)

Evolving Future Combat Vehicle MNS
- A Multi-Mission Combat System -

Goal:
An advanced ground fighting system integrating multi-mission needs

Desired Characteristics:

- ***Capable of surviving first round hit***
- ***Affordable***
- ***Maximize commonality***
- ***Unrestricted transportability***
- ***Reduce sustainment reqt's by up to 90%***
- ***Joint & international interoperability***
- ***Embedded training & human factors emphasis***

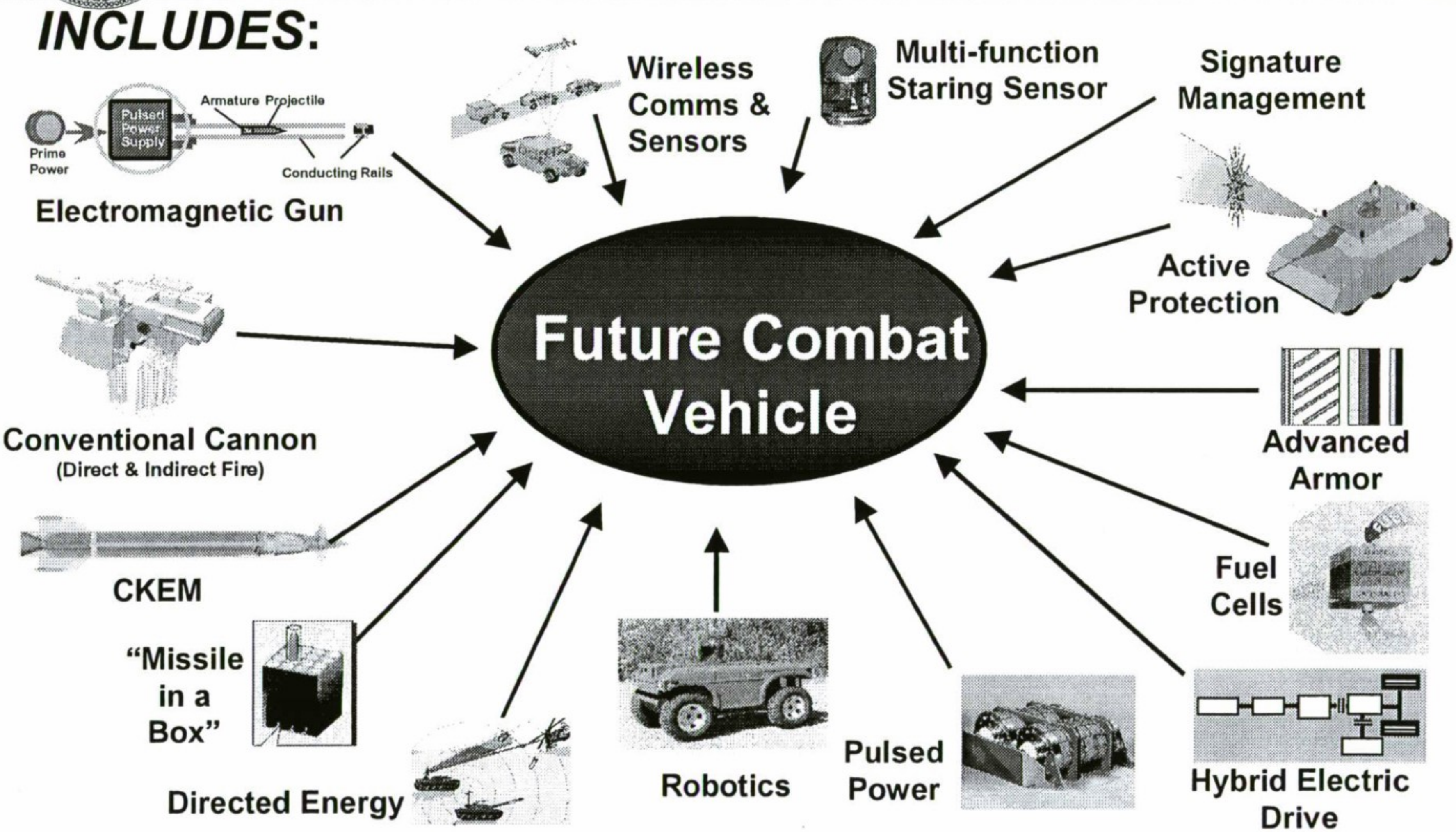
Becomes Urgent Between 2015-2025

FCV Power/Propulsion/Mobility Desired Characteristics

- Up to 200% increase in tactical mobility
- Improved battlefield agility … faster cross-country/road
- Reduced signature (e.g., acoustic, thermal)
- Significantly reduced logistical/sustainment requirements (e.g., fuel, maintenance) by up to 90%
- No weight goal specified … probably under 30 tons, possibly under 20 tons
- No preconceived notion on configuration (wheel, track, or other)
- Many power consumers, some potentially very large (many MJ)

Innovative propulsion technologies are vital to achieve User's vision for FCV

Draw From the Fullest Range of Challenging Technology Options



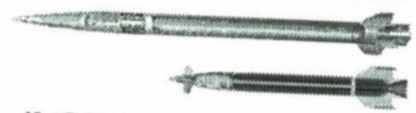
Options to Achieve Revolutionary Capabilities

Lethality

INCLUDES:

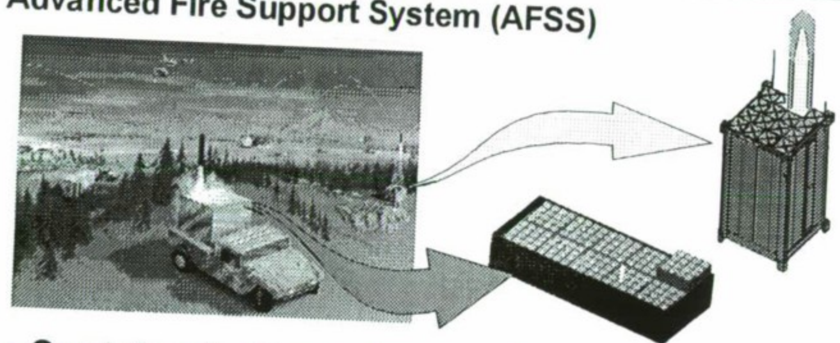
Compact Kinetic Energy Missile (CKEM)

	LOSAT	CKEM Testbed Configuration
Diameter (in)	6.4	6.5
Length (in)	113	72
Weight (lbs)	174	100



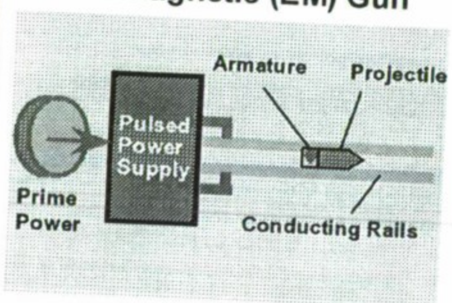
- Overwhelming lethality (LOSAT derivative)
- Light vehicle compatible
- Lightest approach for tank-like (quick) lethality

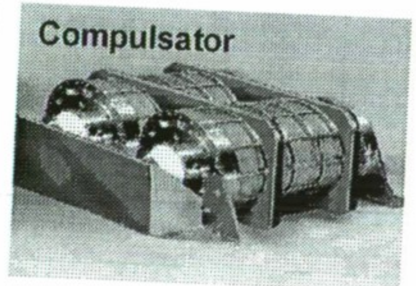
Advanced Fire Support System (AFSS)



- Containerization achieves logistic efficiency
- Provides immediate lethality over a large zone
- Low cost through commonality components

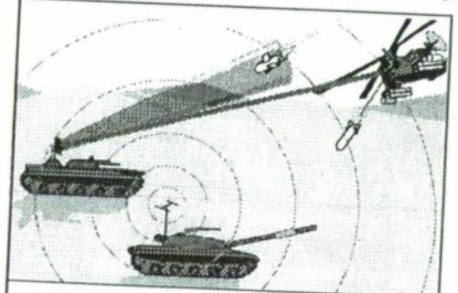
Electromagnetic (EM) Gun





- Hypervelocity launch
- Logistics advantages (propellantless ammo)
- Very large pulsed power requirements

Directed Energy Weapons (high power microwave, lasers)

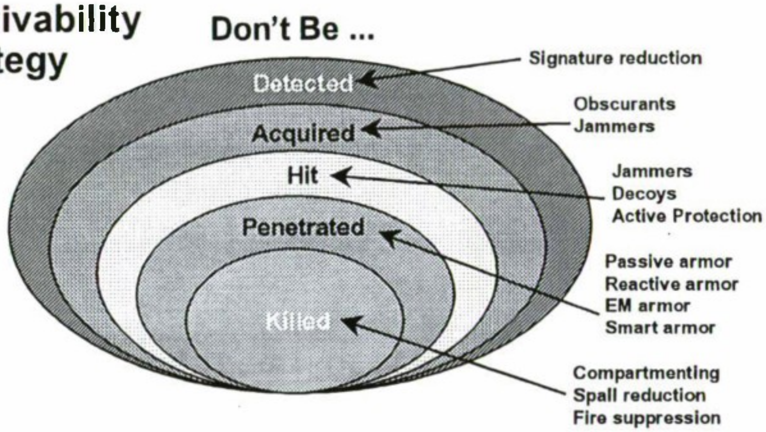


- High power requirements
- Defensive applications (e.g., jamming) viable

Multiple technology options & challenges

Survivability

Survivability Strategy



Signature management

- All spectra
  - Near-Far IR
  - Radar
  - Acoustic
  - Visible
- Treatments
  - Shaping
  - Coatings
  - Advanced materials

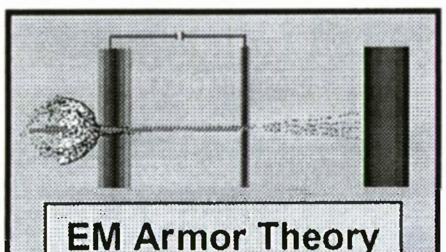
Easier

- Challenges
  - System burden
  - Cost
  - Durability
  - Reliability
  - Classification

Armor

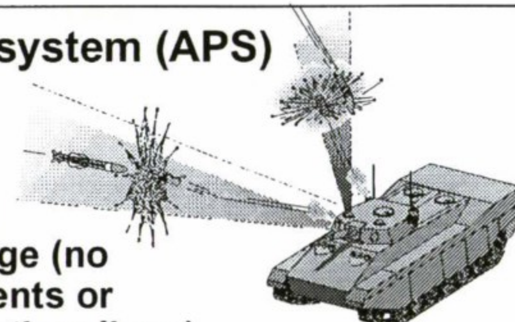
- Advanced armor technologies (advanced ERA, EM armor, and Smart Armor) could reduce armor weight by ~2/3
- Need "medium" armor capability to avoid "cheap kills" and handle APS residuals

Moderate (KJ) pulse power requirements for EM armor



EM Armor Theory "Walker Plates"

Active protection system (APS)



- ATGM proven, some available on world arms market
- KE tougher challenge (no electronic components or explosives, shorter time lines)
- Lightest approach for improved protection
- Potential to make some weapons obsolete!
- Needs medium armor backup to catch residual effects of successful APS engagement

Power needed for actuators, sensors

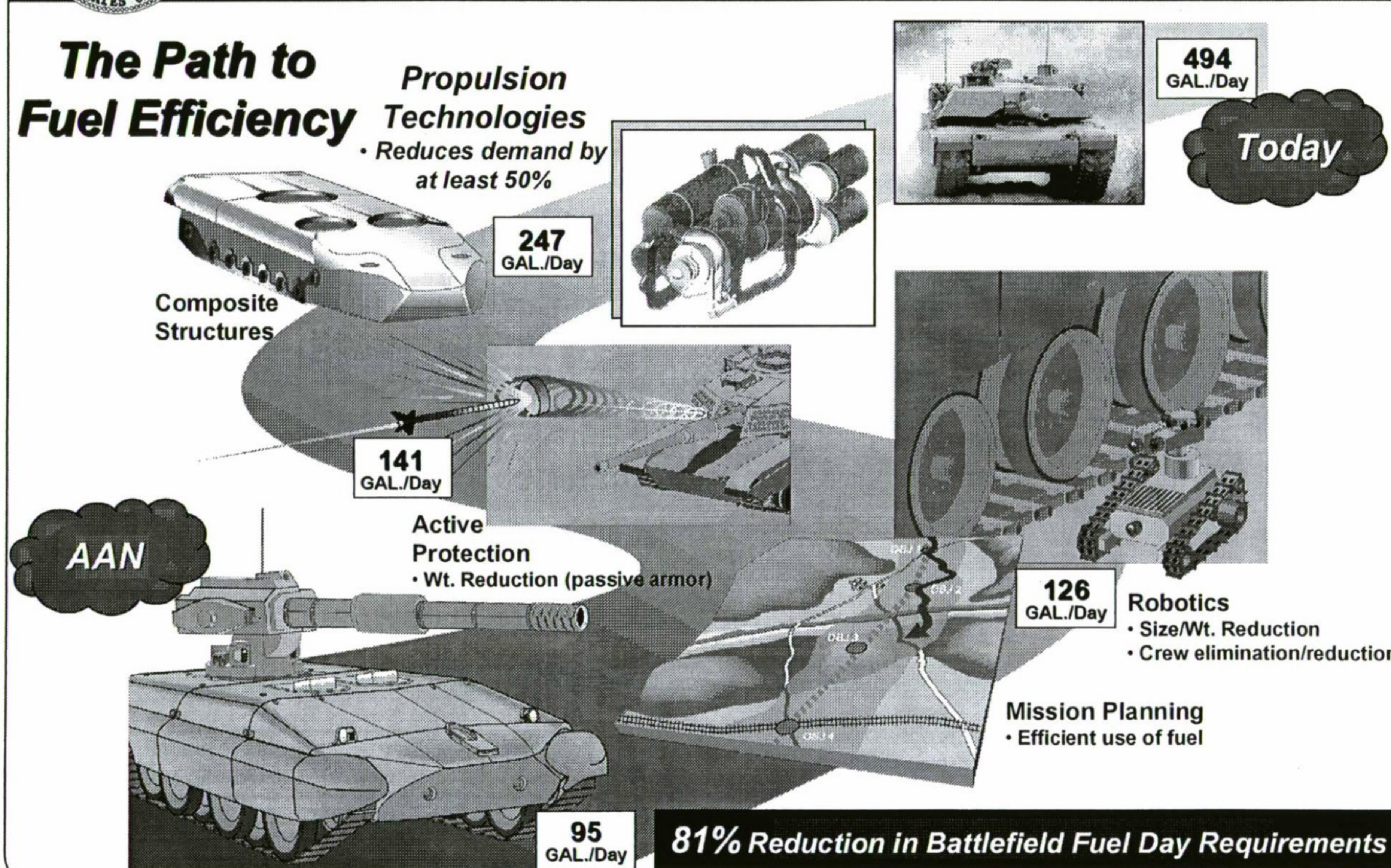
Traditional survivability ... a major challenge for lighter combat vehicles

Vehicle Propulsion

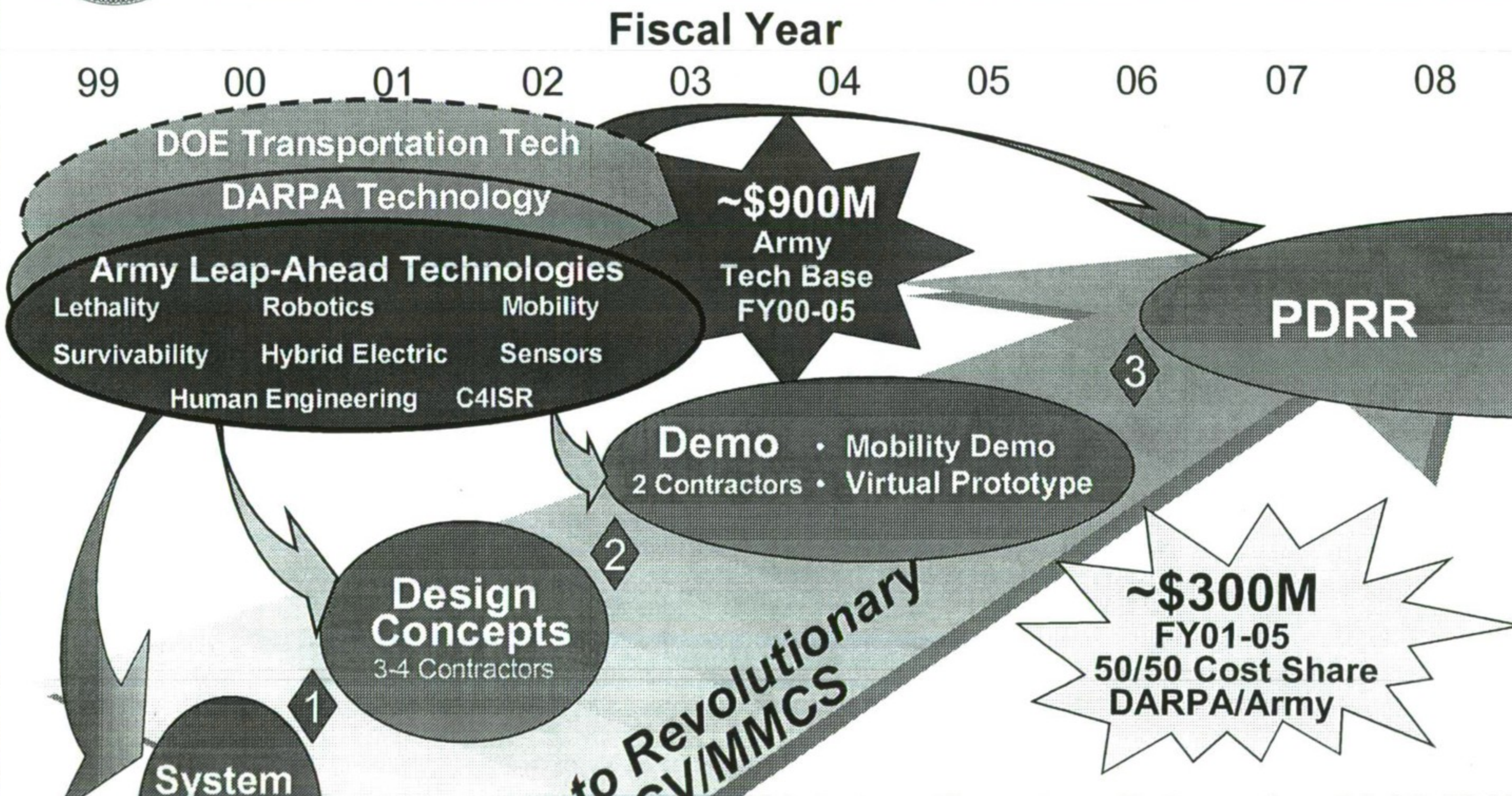
Easier

	Pro:	Con:
• Advanced Diesel/Turbine	• Low risk, > 2x fuel economy & < 1/2 volume of AGT1500	• Evolving capability (not revolutionary)
• Electric Drive	• Greater automotive performance, high commercial interest, system design flexibility, limited silent operation	• Thermal management, unsure commercial base
• Hybrid Electric Power	• Power leveling, energy for continuous & pulse power, silent watch, smaller engine, higher vehicle performance	• Thermal management, complex controls, cost, energy storage durability
• Fuel Cells	• Silent ops, high energy efficiency, low polluting	• High technical risk for fuel reformer to use military standard fuels, unsure commercial base

Reducing Logistics Demand



Future Combat Vehicle
Potential DARPA/Army Program



Decision Events - Driven by 2018 FUE

1. Launch Revolutionary Program with DARPA
2. Pursue Feasible & Affordable Approach
3. Meet Milestone I Requirements

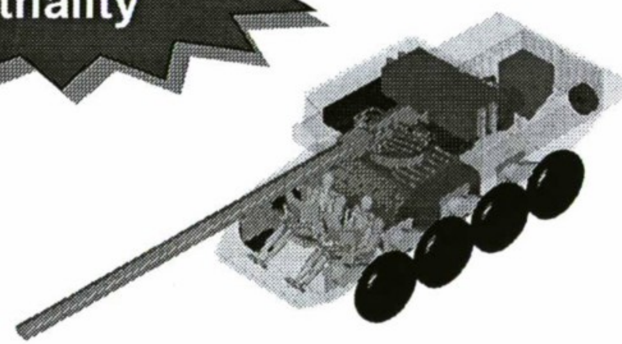
With Success -- The Impact

- Revolutionary Logistics
  - » Fuel efficiency
  - » Minimal sustainment
- Revolutionary Mobility
  - » Enhanced strategic deployability
  - » Greater tactical mobility
- Revolutionary Lethality
  - » Significant increase in stowed load
  - » Diversity of lethality options
- Revolutionary Survivability
  - » Harder to see
  - » Harder to kill

1998 ASB Summer Study View
- 3x increase in effectiveness
- 3x increase in mobility
- 1/3 of today's support

Dominate the Battlefield

Leap Ahead Lethality



Revolutionary Performance for AAN Combat System

Summary

- ✓ Clear FCV goals -> demo by FY05
- ✓ Radical change from current capability
- ✓ Aggressive risk taking for high payoff capability
  - ✓ Substantive technical challenges
  - ✓ Revolutionary capability
- ✓ Clear transition path to FCV PDRR
- ✓ Developing DARPA/Army Partnership

Propulsion technology will be a critical enabler of a revolution in land warfare

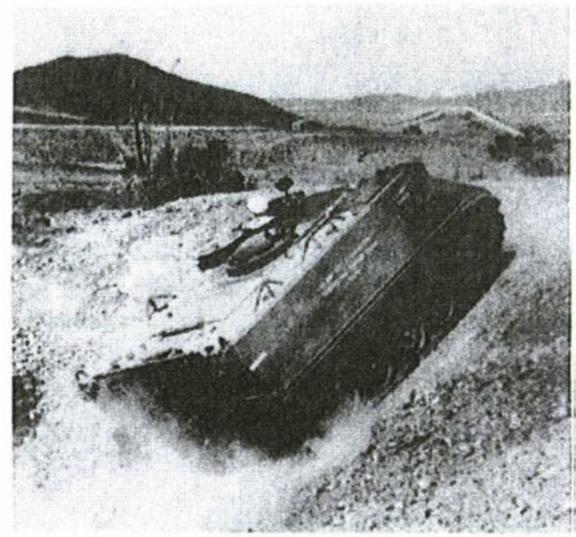
NDIA
ALTERNATIVE PROPULSION SYMPOSIUM

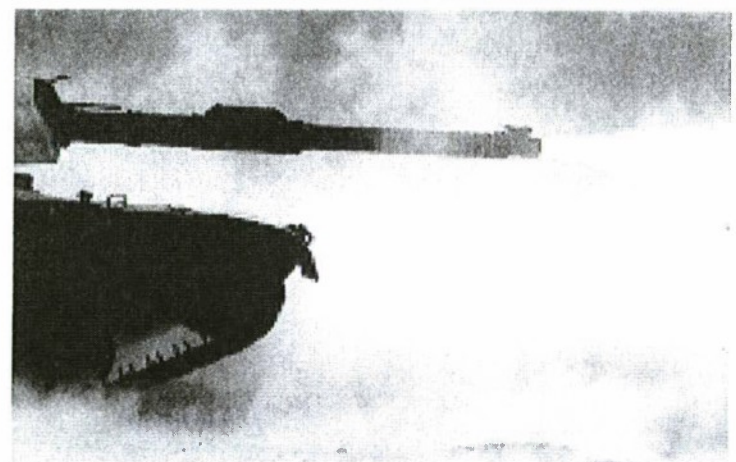
May 4-5, 1999

Jerry L. Chapin
Director
TARDEC

Military Environment

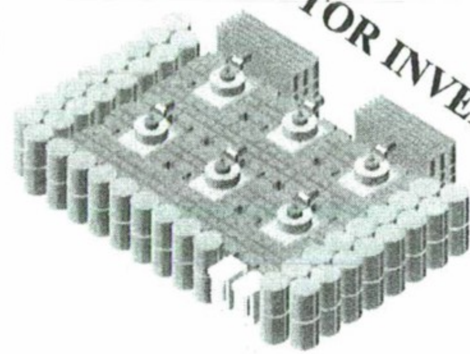
- Up to 60% grade
- Continuous down hill braking on 15% grade
- Top speed up to the suspension and power limits
- Gap and obstacle crossings
- Extreme ambient temperatures
- Gun firing





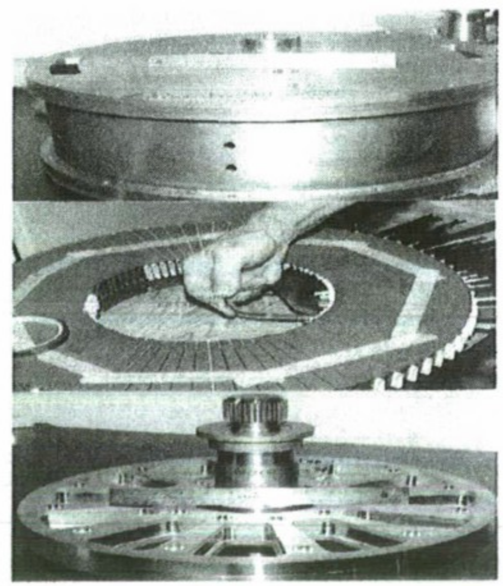
PROGRAM OBJECTIVES

MOTOR INVERTER



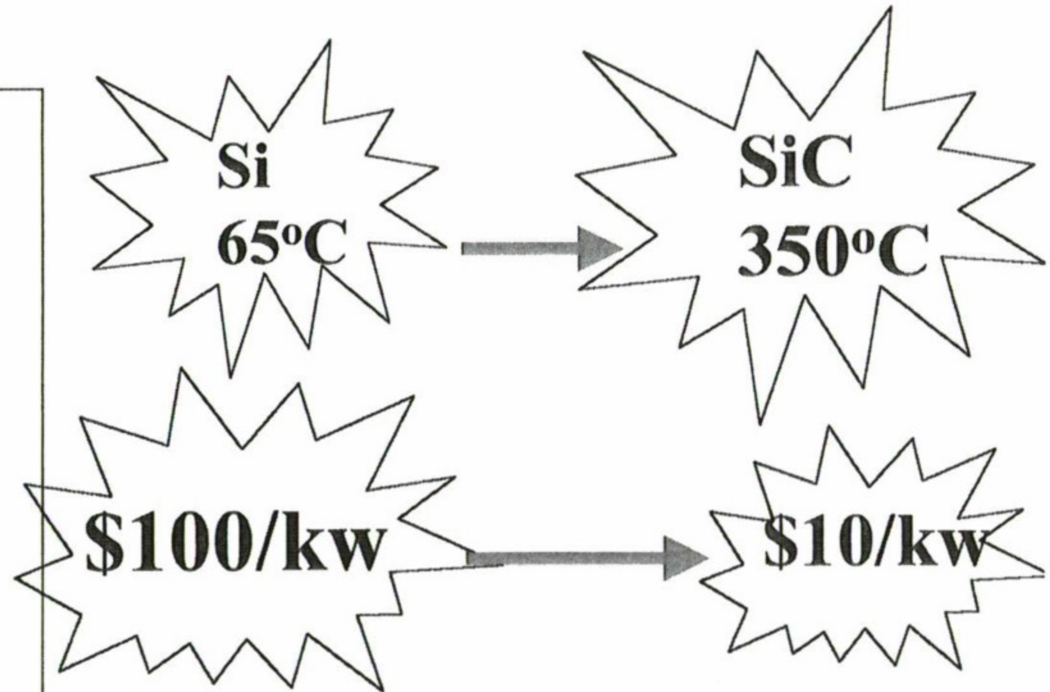
- Stretch current technology
- Advance enabling technologies

SBIR PHASE II
HIGH TORQUE DENSITY MOTOR (1600 FT-LBS/FT^3)



CHALLENGES

- Thermal management of semiconductors
- Cost of advanced components
- Reliability for sustainable field operations

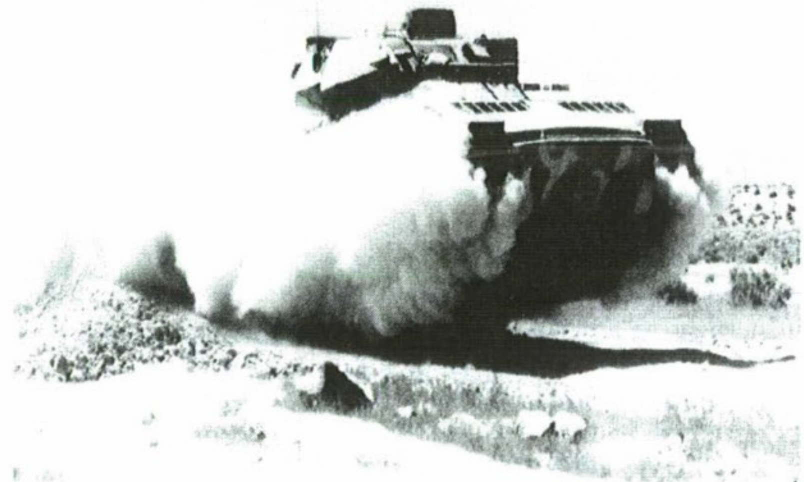


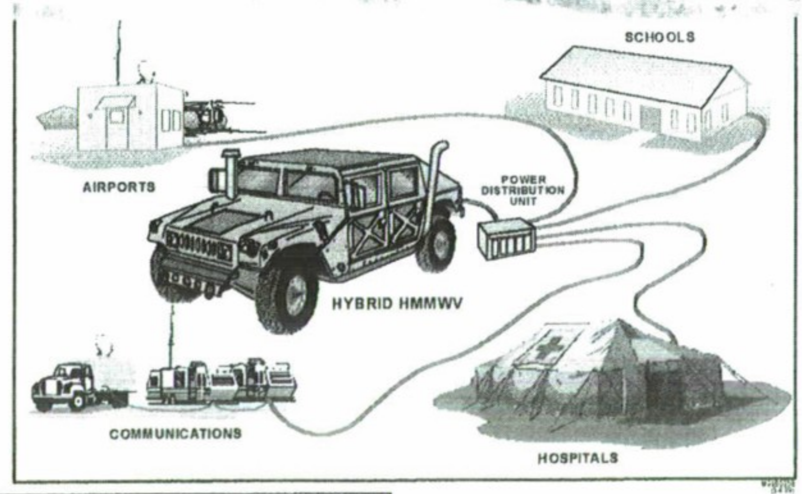
Power electronics

VISION

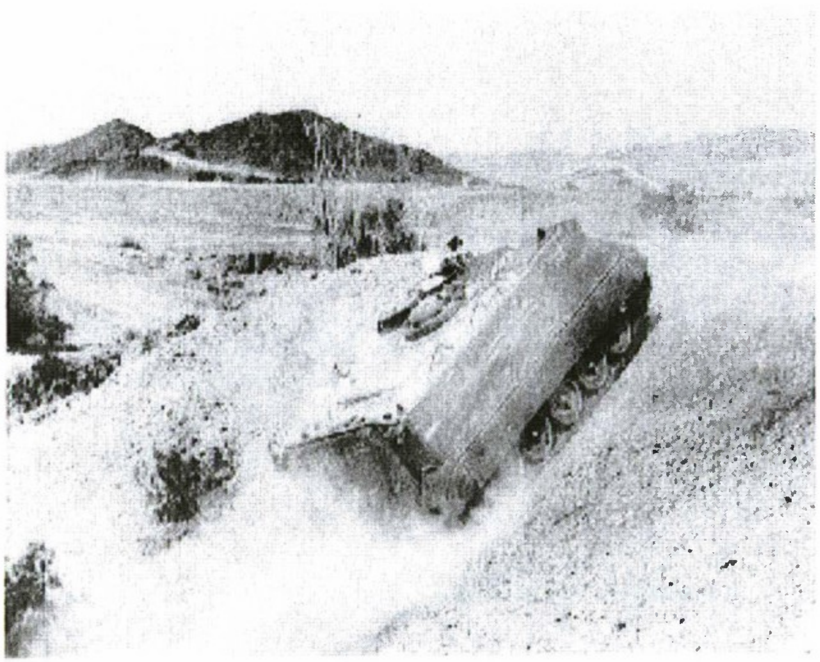
Hybrid drives are the means to:

1. Better performance
2. Reduced fuel and reduced logistics
3. Expanded mission capabilities





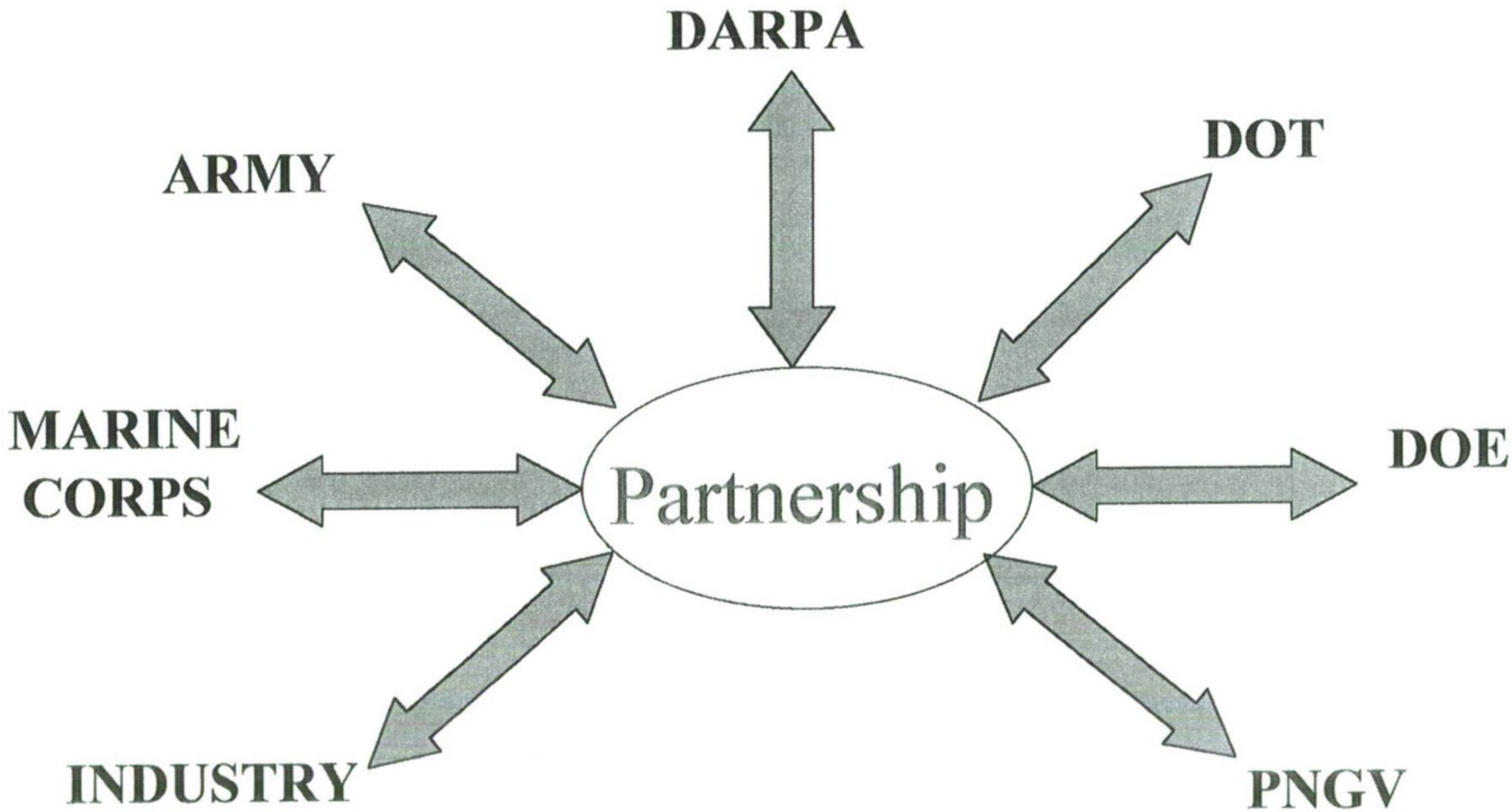
STRATEGY



- **Systems Integration**
- **Verify hybrid drive benefits through Modeling, Simulation and testing:**
  - Fuel economy
  - Mobility Performance
  - Power availability
  - Stealth operation
- **User involvement and evaluation**

TACOM
Mobility and Firepower for America's Army

IMPLEMENTATION



TACOM

Mobility and Firepower for America's Army

APPROACH

1

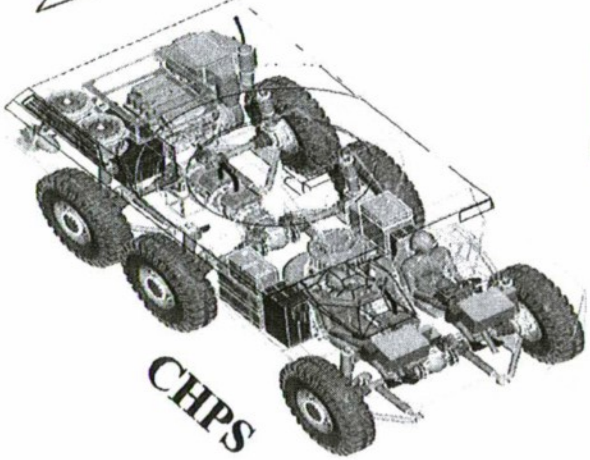
Leverage dual use programs

2

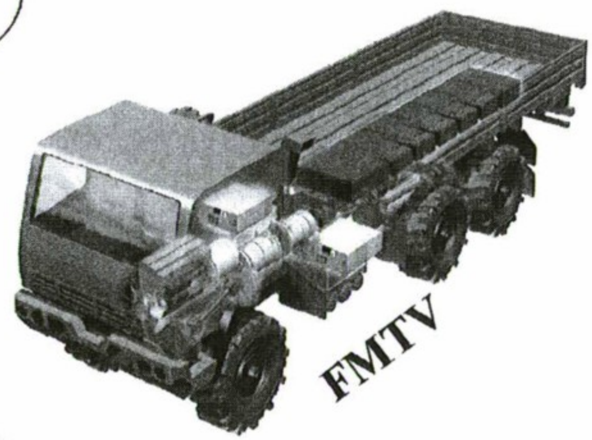
Demonstrate advanced components on military vehicles

3

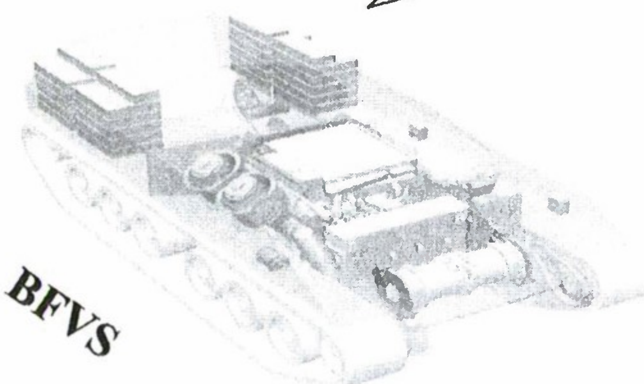
Support Technology Development



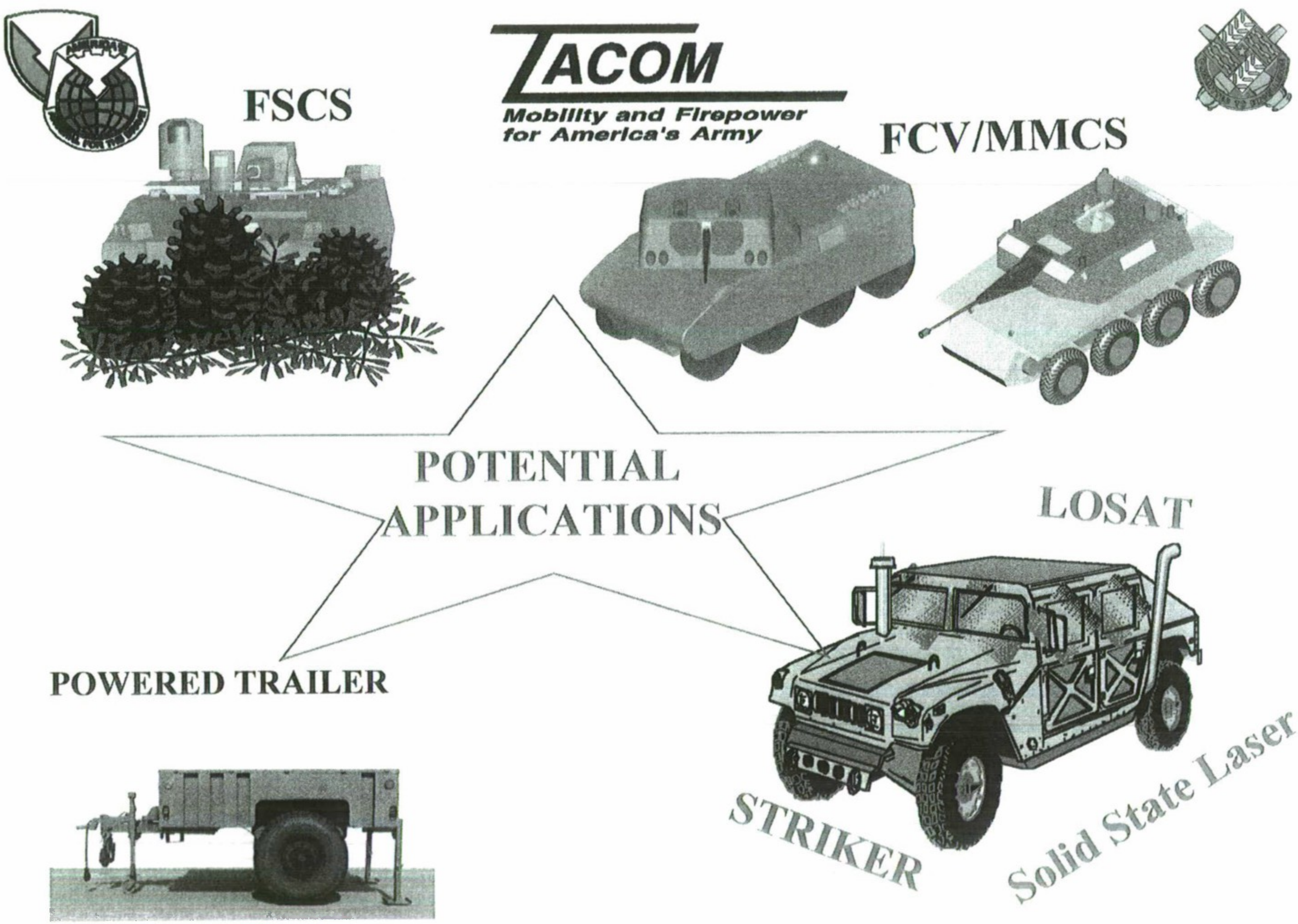
CHPS



FMTV



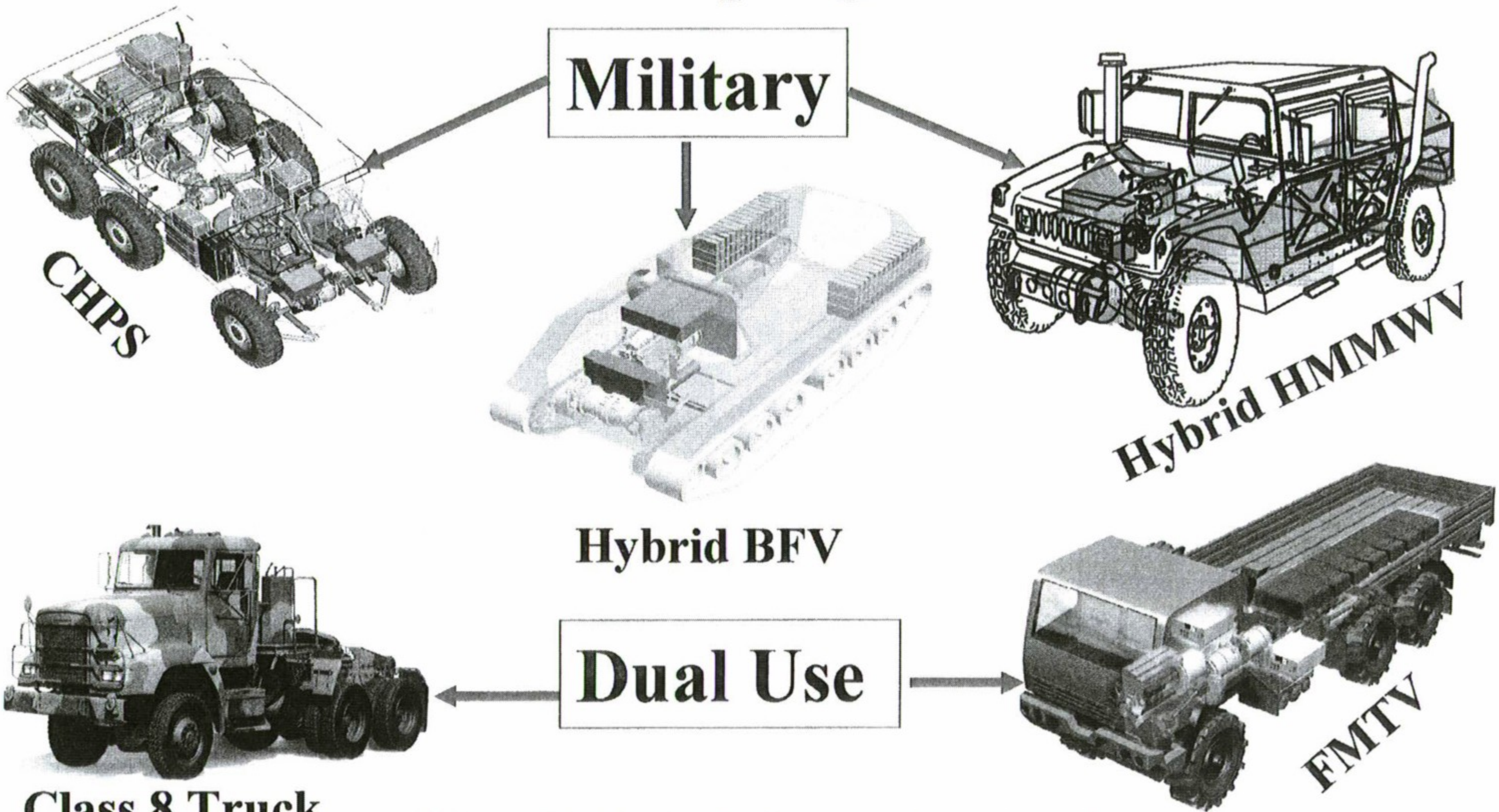
BFVS



Tank-automotive & Armaments COMmand

TACOM
Mobility and Firepower for America's Army

Current programs



SUMMARY

- Benefits of Hybrid electric are needed for future military vehicles
- TACOM is committed to advance the technology and field hybrid vehicles
- Focus is on user's requirements of stealth operation, power supply, better performance, fuel economy and reduced logistics burden

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NDIA - VEHICLE TECHNOLOGY CONFERENCE

DEARBORN, MICHIGAN

MAY 3 - 5, 1999

LITHIUM ION BATTERIES FOR HIGH POWER & HIGH ENERGY ADVANCED TECHNOLOGY APPLICATIONS

SAFT

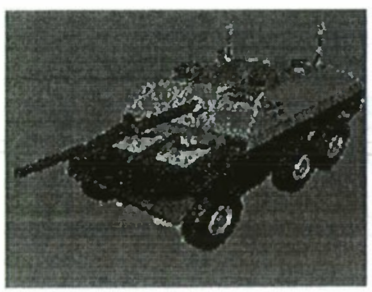
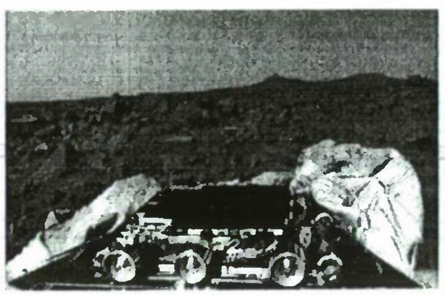
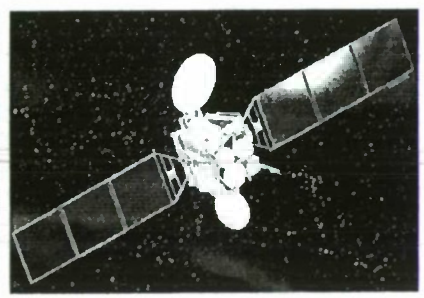
Our Mission

To provide the most advanced power solutions for advanced technology systems

SAFT

Our Commitment

The SAFT R & D Center is committed to developing advanced cost-effective, power and energy storage systems to address new challenges in a broad vista of new technologies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Our Main Customers

Ford

Chrysler

GM

Lockheed Martin

US DOE

DARPA

Boeing

Northrop Grumman

Black & Decker

Army/Air Force

NASA

Peugeot

USABC

Orbital Space

TRW

Renault

Loral

Jet Propulsion Lab

SAFT

SAFT Batteries for High Power and High Energy Applications

SAFT

SAFT Expertise

20 Years of Continuous R & D in the Field of Advanced Battery Systems for Electric & Hybrid Vehicle Applications has resulted in:

Ni-CD → In Mass Production

Ni-MH → Ready for Production

Li-Ion → In Development

SAFT

A breakthrough in battery technology

Innovation in the field of high energy batteries

ELECTROCHEMISTRIES		Lead A.	Ni-Cd	Ni-MH	Li-ion Battery	Li-Ion Targeted
Specific Energy	Wh / kg	28	50	64	*80*	*140*
Energy Density	Wh / l	73	80	135	*175*	*310*
Power	W / kg	75	120	140	*200*	*350*
Price	$ / kWh	155	525	385	*750*	*175*
AVAILABILITY	- prototype	1950	1995	1996	1999	1999
	- industrial			1999	2000	2002

Note: $175/kWh for Li-ion produced on a large industrial scale (100 000 batteries / year)

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Two major battery development programs

Since 1993

in Poitiers / Bordeaux

ELECTRIC VEHICLES

France & Europe :

- **Joule program**
- **Vedelic**
- **VE2000**
- **other programs**

$25M

Since 1996

in Cockeysville, MD

HYBRID ELECTRIC VEHICLES

North America :

- **PNGV (USABC/DOE)**
- **Dept of Defense -**
  - **DARPA**
    - **CHPS**
  - **RST-V, FCS**

$16.5M

support and main programs

external funding

SAFT

Saft's Li-ion Cell Range : the full spectrum of performance

Cell Name	High Energy HE-44Ah	Dual Mode DM-30Ah	High Power HP-12/6Ah	
Energy *Wh/kg*	140	100	70	64
Power *W/kg*	300	950	1350	1500
P/E ratio	2 to 3	8 to 10	18 to 25	
Applications	EV	HEV with ZEV	HEV PA / Starter	

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The Li-ion High Energy Program

A comprehensive product development plan

1993 - 96	1996 - mid 99	mid 99 - 01	2001 - 03
Phase 1 FEASIBILITY	Phase 2 PROTOTYPE	Phase 3 FLEET TESTS	Phase 4 COM. LAUNCH
▼ Suitable technology for EV application	▼ Complete battery system with BMS/TMS	▼ Pilot fleets for validation / qualification	▼ Industrial production tools
▼ Standardized dimensions	▼ Prototyped cars on the road	▼ 1st integration on serial cars	▼ marketing test (specific users)

In parallel : continuous improvements of the electrochemical technology

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Battery Module Concept

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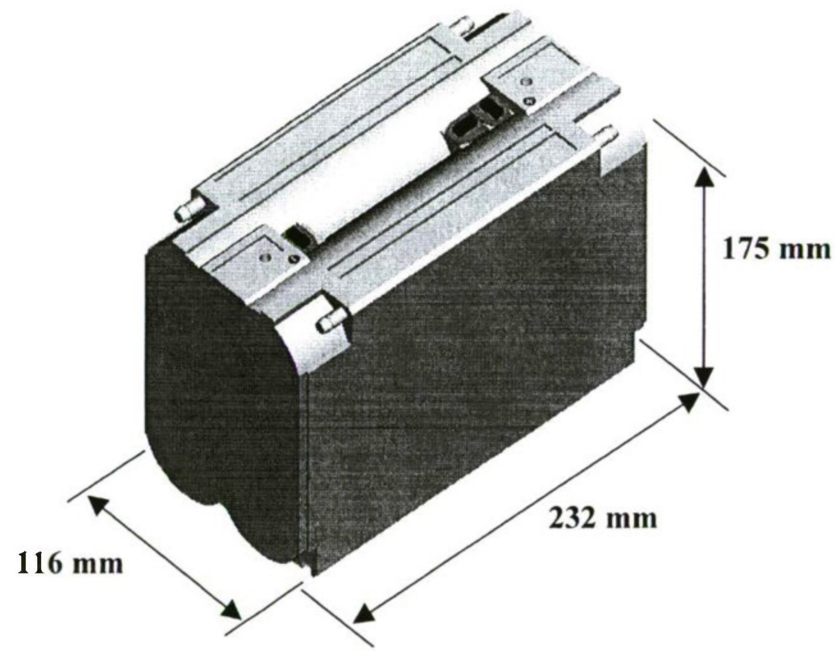
High Energy Module



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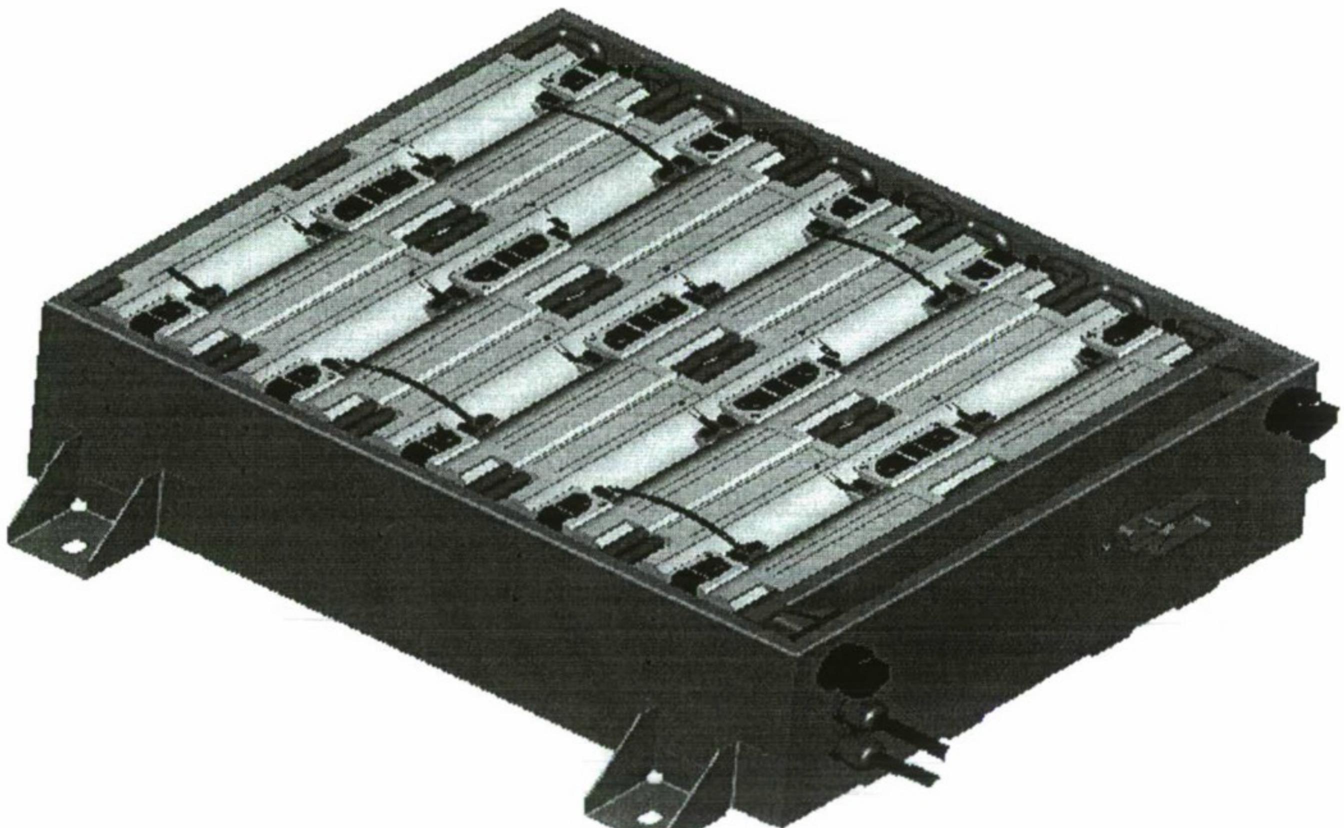
Battery Pack 10 Module Configuration



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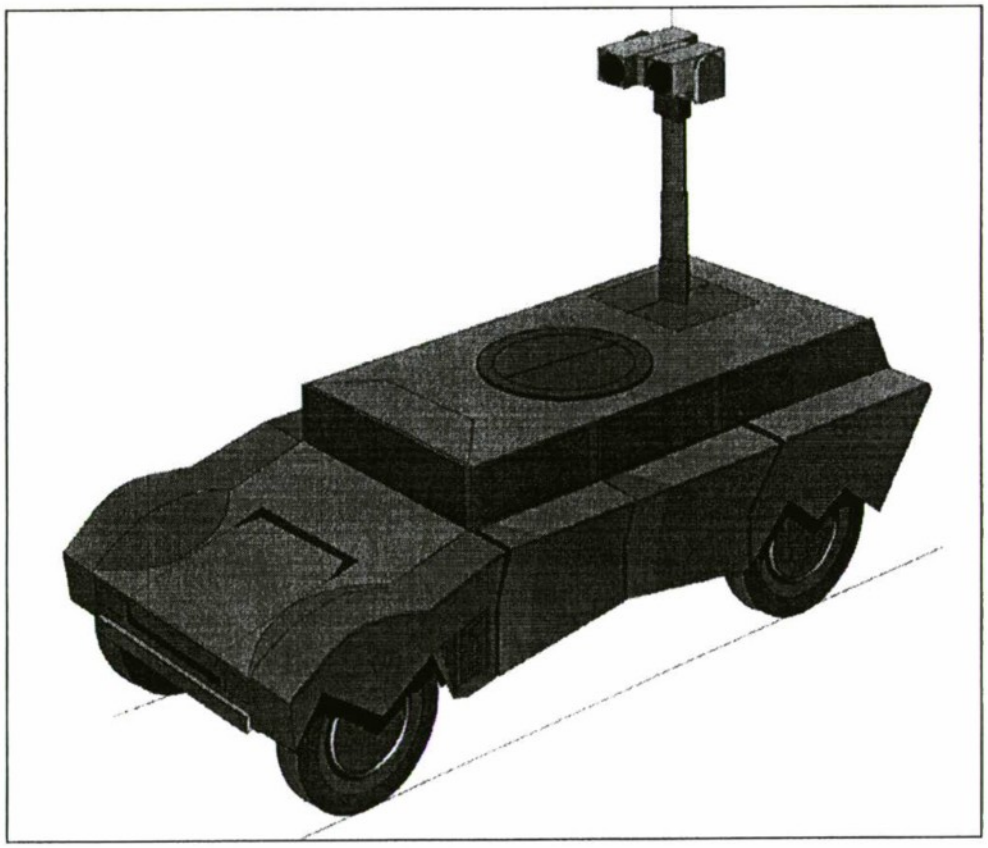
RST-V Concept Vehicle



SAFT

Market Potential for Lithium Ion Technology

- Lithium Ion technology has been the fastest growing portable technology ever introduced

- Lithium Ion technology has shown rapid price reduction in the commercial market

  1992 > $18 per 18650 Cell
  1999 < $ 2 per 18650 Cell

- Many of the processes or equipment that would be utilized on “Commercial or Military” Lithium Ion products are used today in portable lithium ion assembly
  - two sided coating
  - high speed calandering
  - high speed winding

- Multiple products can be made from a common facility

SAFT

INDUSTRIAL ROAD MAP FOR HIGH POWER AND HIGH ENERGY BATTERY CELLS

A COMMON APPROACH

- SAME STANDARD BASIC COMPONENTS (Electrochemistry)
- SELECTED SUPPLIERS
- SIMILAR CELL DESIGN
- POSSIBLE COMMON PRODUCTION PLANT

SAFT

The Li-ion High Power Program

An accelerated technical development

1996	1997 - mid 99	mid 99 - 00
Phase 1 FEASIBILITY	*Phase 2* DEVELOPMENT	*Phase 3* COST REDUCTION

- Evaluation & feasibility of hybrid Li-ion
- electrical and safety validation

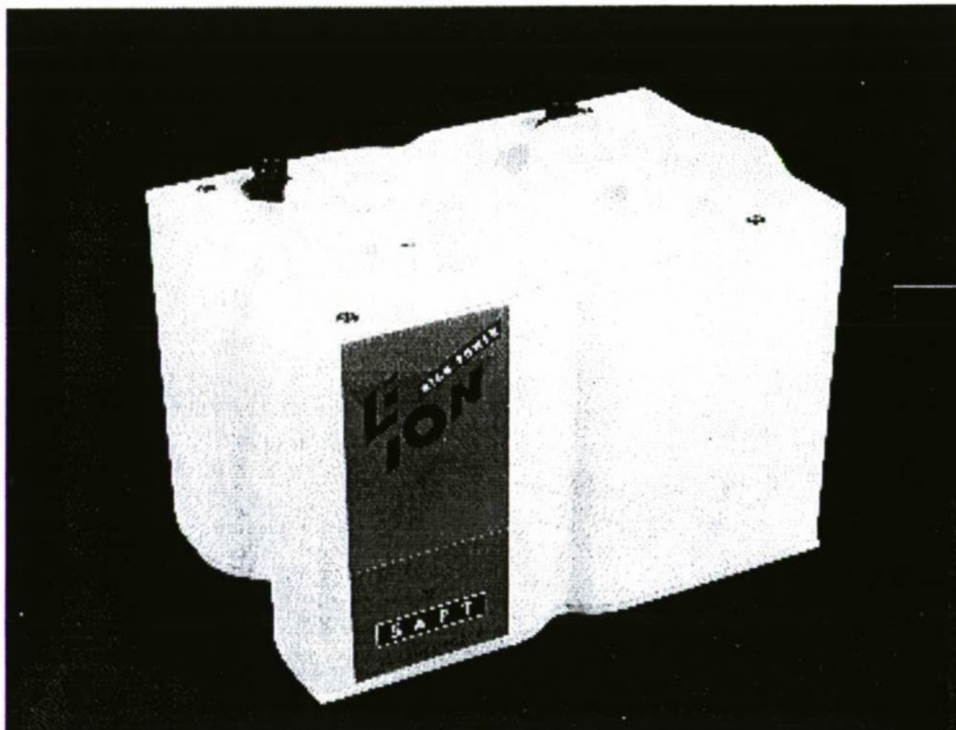
- Standard cells
- 42 V standard module with electronic control & cooling system

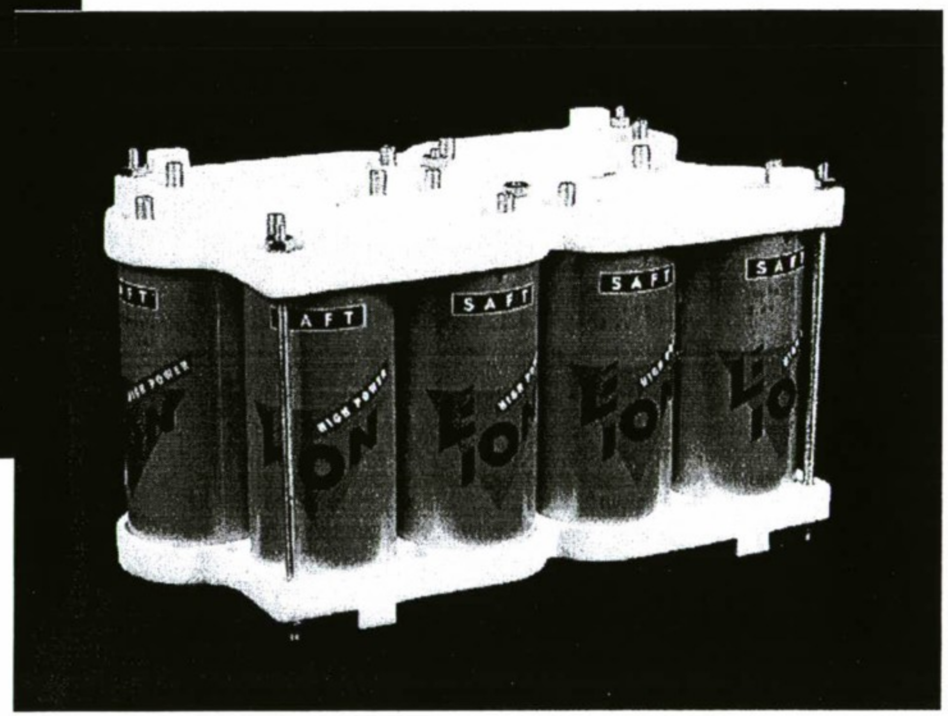
In parallel with car makers : Battery integration on project vehicles

And initiated by Saft to prepare the industrialization engineering studies

SAFT

High Power Module Concept





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LITHIUM ION ELECTROCHEMISTRY

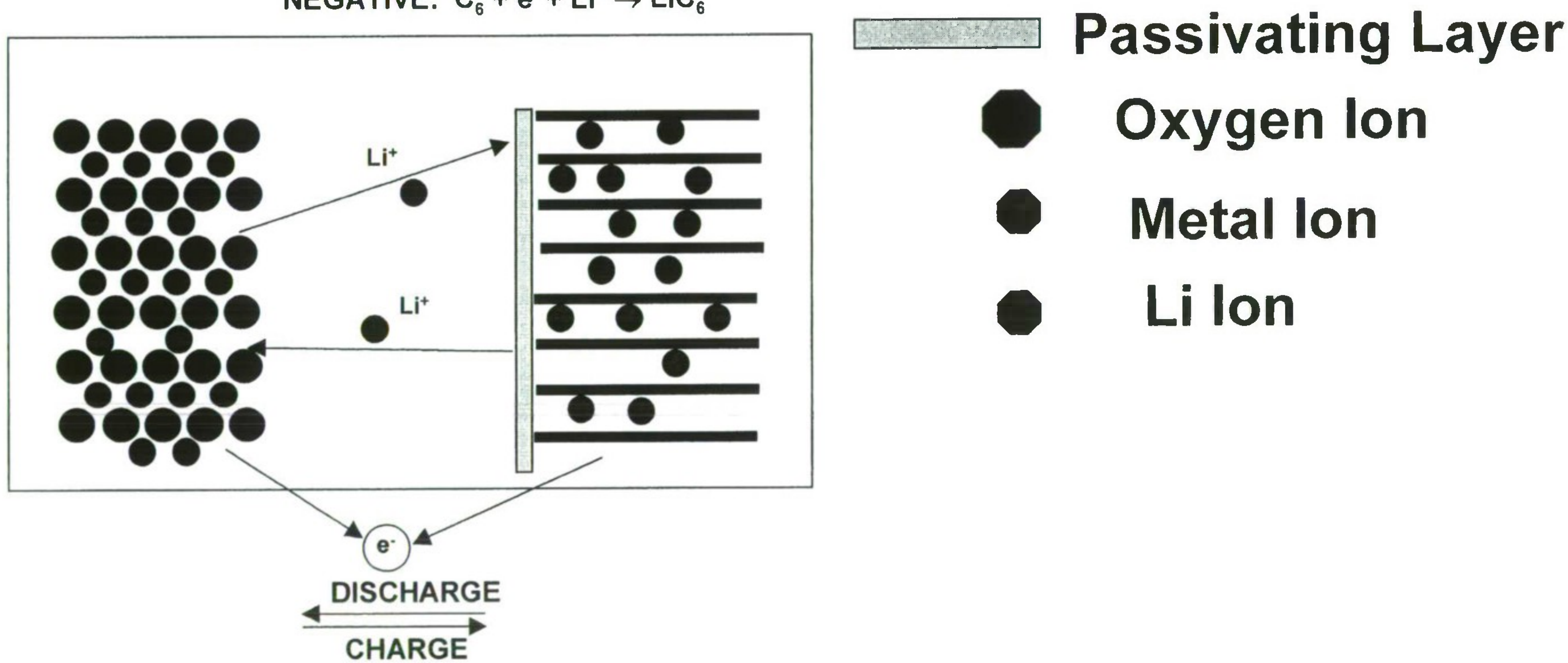
LITHIUM ION BATTERIES UTILIZE A 'ROCKING CHAIR' CHEMISTRY, i.e., LITHIUM ION ROCKS FROM THE POSITIVE TO THE NEGATIVE.

POSITIVE: $LiMO_2$ (M = Co, Ni, Mn OR ALLOYS) IS THE SOURCE OF ALL LITHIUM IONS.

NEGATIVE: VARIOUS CARBONS OR INTERCALATION MATERIALS.

ON CHARGE: POSITIVE: $LiMO_2 \rightarrow x\ Li^{(+)} + xe^- + Li_{1-x}MO_2$

NEGATIVE: $C_6 + e^- + Li^+ \rightarrow LiC_6$



SAFT

TECHNOLOGY TODAY

HIGH POWER LiON® CELL CYCLE LIFE DATA

18650 CELLS

- CELL DIAMETER: 18 mm
- CELL LENGTH: 65 mm
- CAPACITY: ABOUT 0.7 Ah

TEST DESCRIPTION

- CELL SET UP AT A STATE OF CHARGE OF 50%
- CONTINUOUS CYCLING AROUND THIS POINT; THE ΔDOD CORRESPONDS TO THE TOTAL VARIATION OF STATE OF CHARGE DURING ONE CYCLE
- CELLS CHARACTERIZED AT REGULAR PERIODS TO VERIFY THE CAPACITY LOSS AND THE IMPEDANCE VARIATION

ΔDOD	CYCLES	CAPACITY LOSS	RESISTANCE INCREASE
1%	1,105,500	0%	0%
10%	107,150	6%	21%
15%	87,500	8%	30%
30%	93,473*	18%	41.2%

*NOTE: AT 71,000 CYCLES RESISTANCE INCREASE IS 31%

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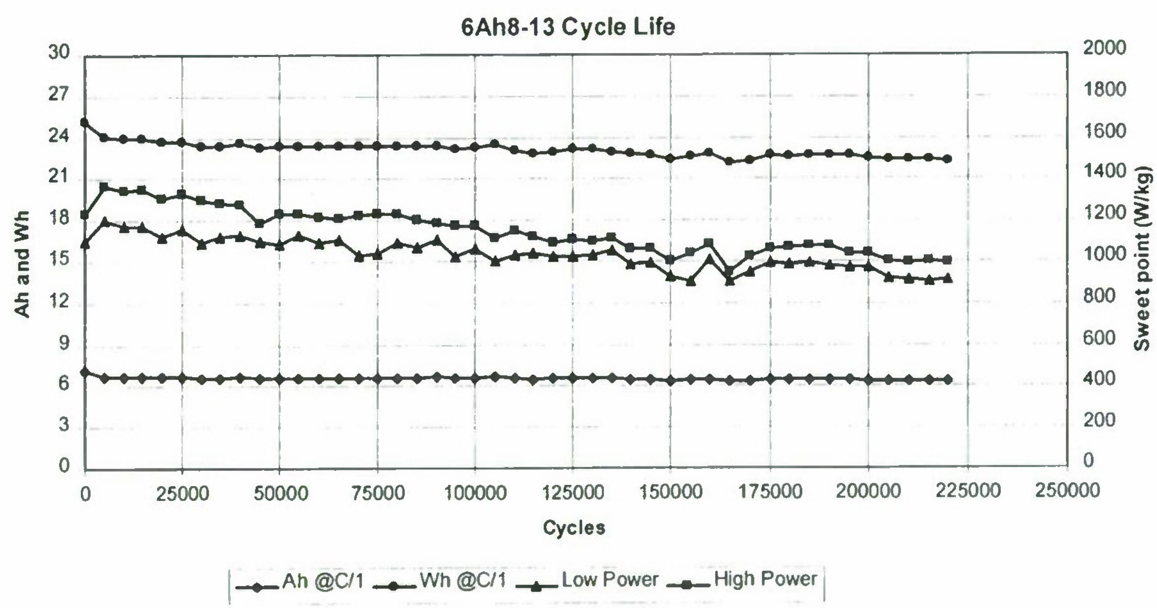
TECHNOLOGY TODAY

HIGH POWER LiON® CYCLE LIFE DATA

<u>HIGH POWER CELL</u>

CELL DIAMETER	47mm
CELL LENGTH	104mm
CAPACITY	About 6 Ah



TEST DESCRIPTION

CELL SET UP AT A STATE OF CHARGE OF 50%

CONTINUOUS CYCLING: ONE MINUTE CYCLE, WITH PEAK CURRENT OF ABOUT 60a AND A CHARGE DISCHARGE CAPACITY RATIO OF 1

CELLS CHARACTERIZED FOR A CAPACITY AND POWER EVERY 5000 CYCLES

SAFT

TECHNOLOGY TODAY

TECHNOLOGY TODAY

CELL TYPE	HIGH ENERGY	HIGH POWER
DIAMETER mm	54	47
LENGTH mm	220	178
VOLUME l	0.5	0.31
MASS kg	1.07	0.68
CAPACITY AT C/3 Ah	44 (35 usable)	13
ENERGY DENSITY Wh/kg	144	70
POWER DENSITY W/k (18 sec. Pulse discharge at 50% DOD)	850	2000
POWER DENSITY W/K (2 SEC. Pulse Discharge at 20% DOD)	1210	3100

SAFT

Strategy for the military, aerospace, and automotive industry

Building successful partnerships

- Advanced Technology programs with a leadership on Li-ion technology.
- A comprehensive product range and modular concept for military, aerospace, and automotive applications.
- Investments in pilot production lines and a willingness to industrialize on larger scale.
- Dedicated scientific and engineering teams, experienced in battery development programs and available for platform implementation.

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Conclusions

- Li Ion Technology for high power and high energy is making rapid progress toward military, aerospace, and commercial availability
- Li Ion can provide the military, aerospace, and automotive industry with both High Power & High Energy solutions for battery applications at reasonable costs.
- Li Ion Technology will allow advanced technology designers greater flexibility.
- The major challenges will be to demonstrate acceptable abuse tolerance, while using dual use commercial applications to reduce costs.

Ovonic NiMH EV and HEV Battery Technology for Military HEV Applications

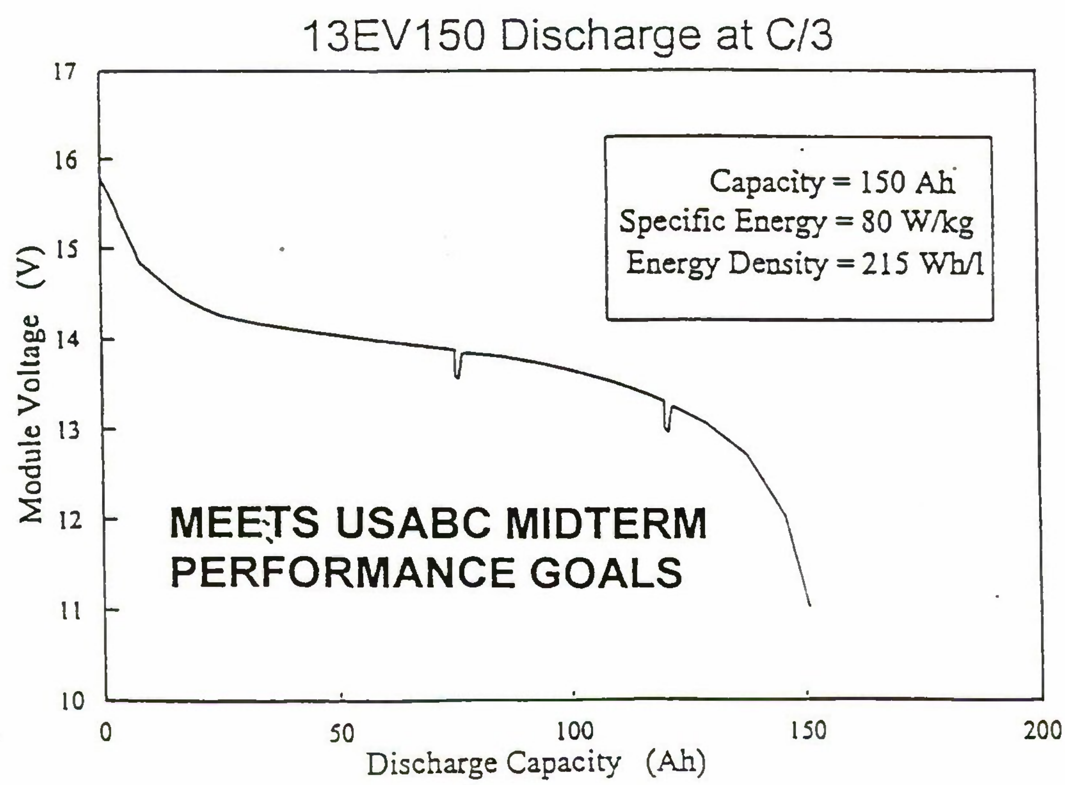
Ivan Menjak
Ovonic Battery Company
Troy, Michigan

Presented at 1999 Vehicle Technologies
Alternative Propulsion Symposium

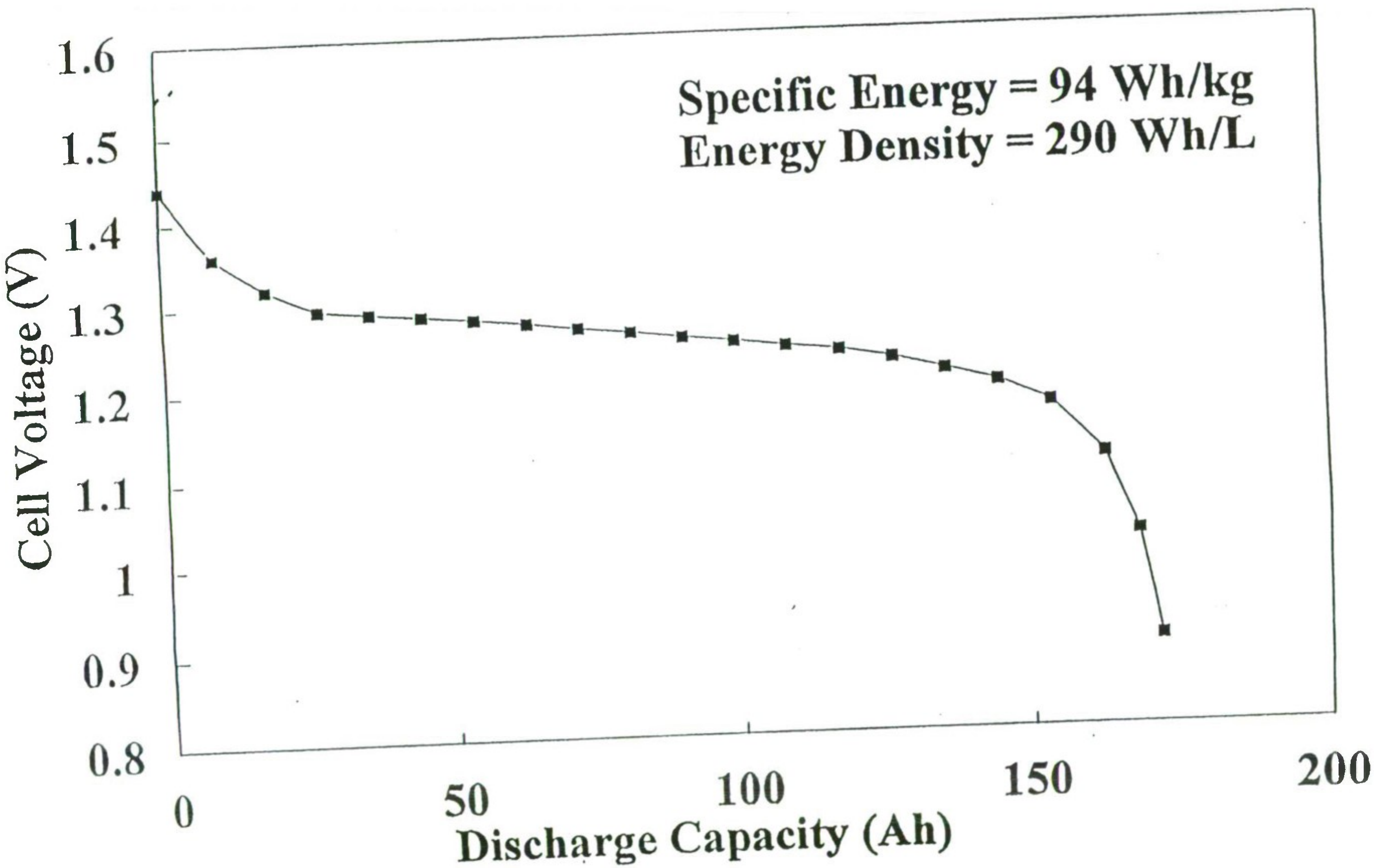
May 4, 1999
Dearborn, Michigan

OVONIC NiMH EV BATTERIES
13-EV-150 BATTERY MODULES

Configuration	11-cell
Dimensions (LxWxH)	423x104x217 mm
Volume	29.5 L
Weight	26 kg
Nominal Voltage	13.2 V
Capacity (C/3)	150 Ah
Energy	2.1 kWh
Power (80% DOD)	6.5 kW
Specific Energy	80 Wh/kg
Energy Density	215 Wh/L
Specific Power	250 W/kg
Power Density	675 W/L
2-Day Charge Retention	92%
Cycle Life (DST)	>600



OVONIC Gen 3 PROTOTYPE EV BATTERY



GM Ovonic

PRODUCT SPECIFICATIONS

Product:	Gen I Design, Model 13-EV-90
Capacity:	90 Ah (C/3)
Energy:	1.2 KWh
Specific Energy:	70 Wh/Kg
Energy Density:	170 Wh/L
Specific Power:	200 W/Kg (30 seconds @ 80% D.O.D.)
Power Density:	485 W/L
Charge Retention:	93% @ 80°F after 48 hours 85% @ 100°F after 48 hours
Operating Temperature:	< 110°F for Maximum Life < 150°F to Avoid Damage
Cycle Life:	600 DST cycles to 80% D.O.D.
Other:	Maintenance Free No Spillable Liquids Recyclable

HYBRID EV BATTERY REQUIREMENTS

Very High Power:
- > 1000 W/L
- > 500 W/kg

Very High Regen Power:
- > 500 W/kg

High Energy Density:
- > 100 Wh/L
- > 50 Wh/kg

High Efficiency

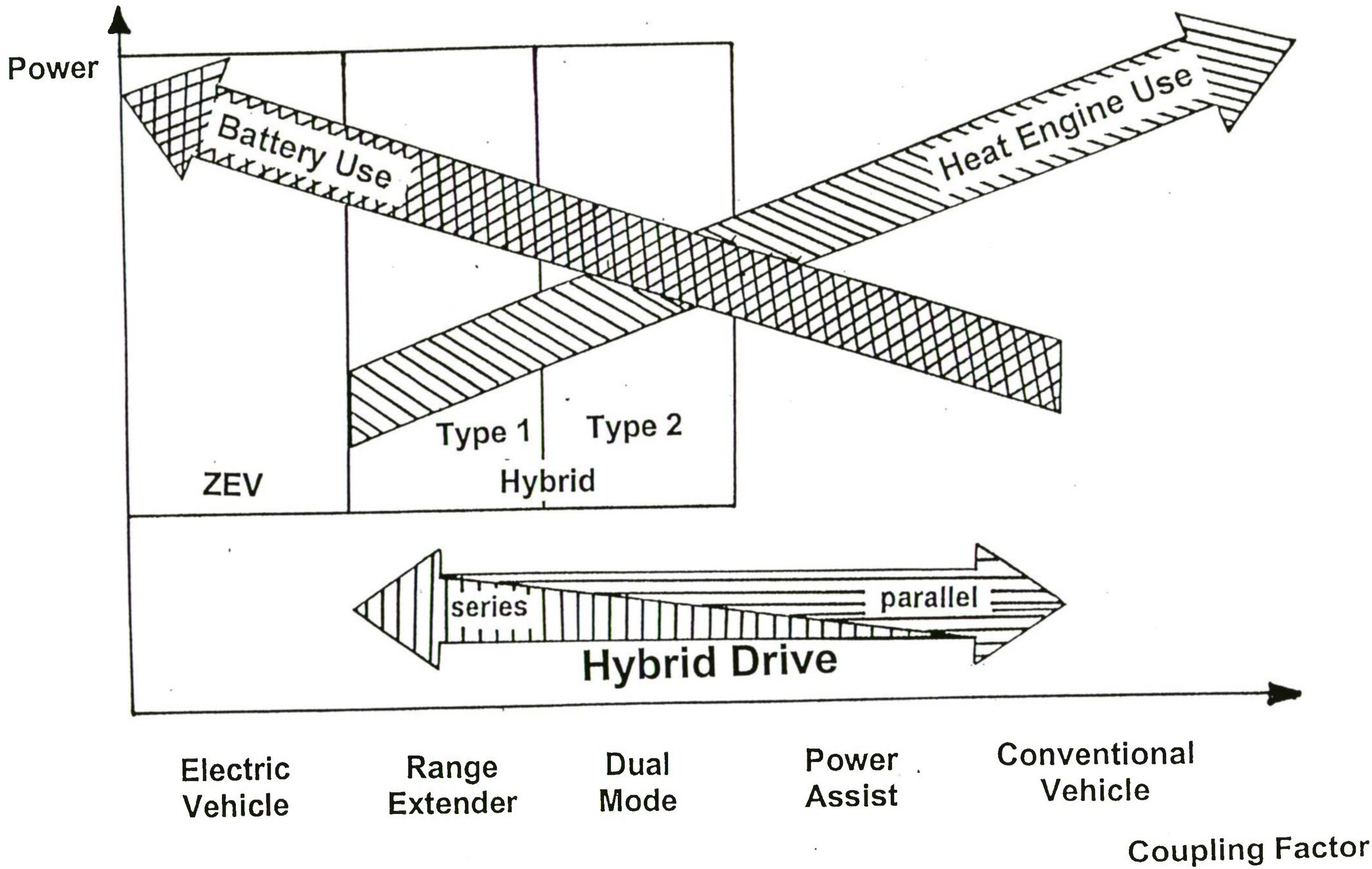
Low Self Discharge

Calendar Life: > 5 Years

High Cycle Life
For EV Mode

Very High Cycle Life
For HEV Mode

Hybrid Drive Layout Options

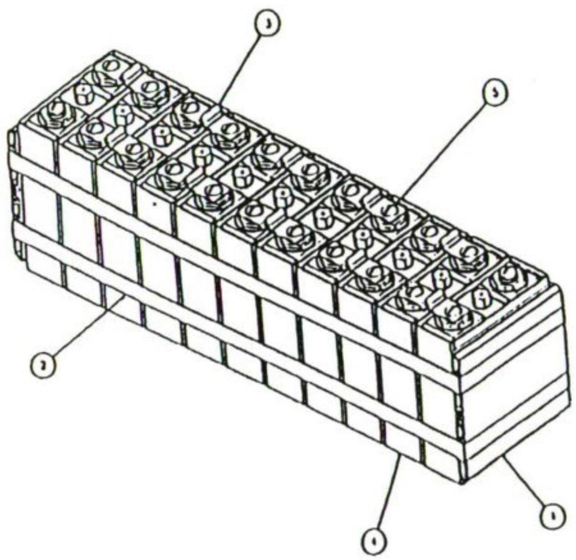


SPECIFICATIONS FOR OVONIC HEV MODULES

	13-HEV-60	7-HEV-28	12-HEV-20
Nominal Voltage (V)	13.2	7.2	12
Nominal Capacity (Ah)	60	28	20
Weight (kg)	12.2	4.3	5.2
Volume (L)	5.1	2.0	2.3
Specific Energy (Wh/kg)	68	50	48
Energy Density (Wh/L)	160	102	110
Specific Power (W/kg)	600	550	550
Power Density (W/L)	1400	1200	1300

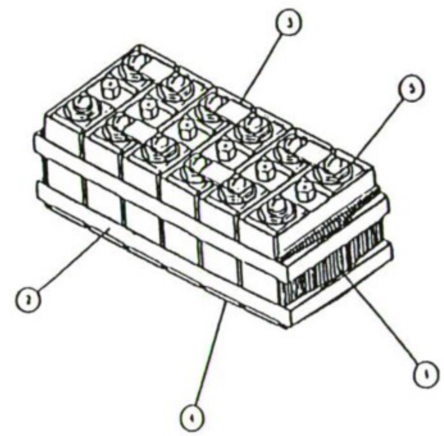
OVONIC NiMH HEV BATTERY MODULES

13-HEV-60
11 cells
60 Ah at 13 V



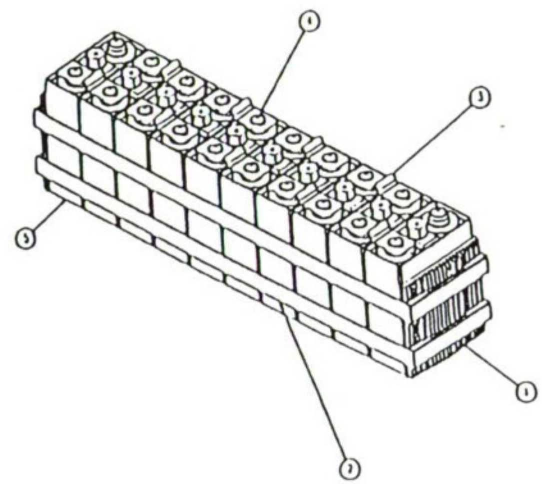
L = 418 mm
W = 102 mm
H = 119 mm

7-HEV-28
6 cells
28 Ah at 7 V



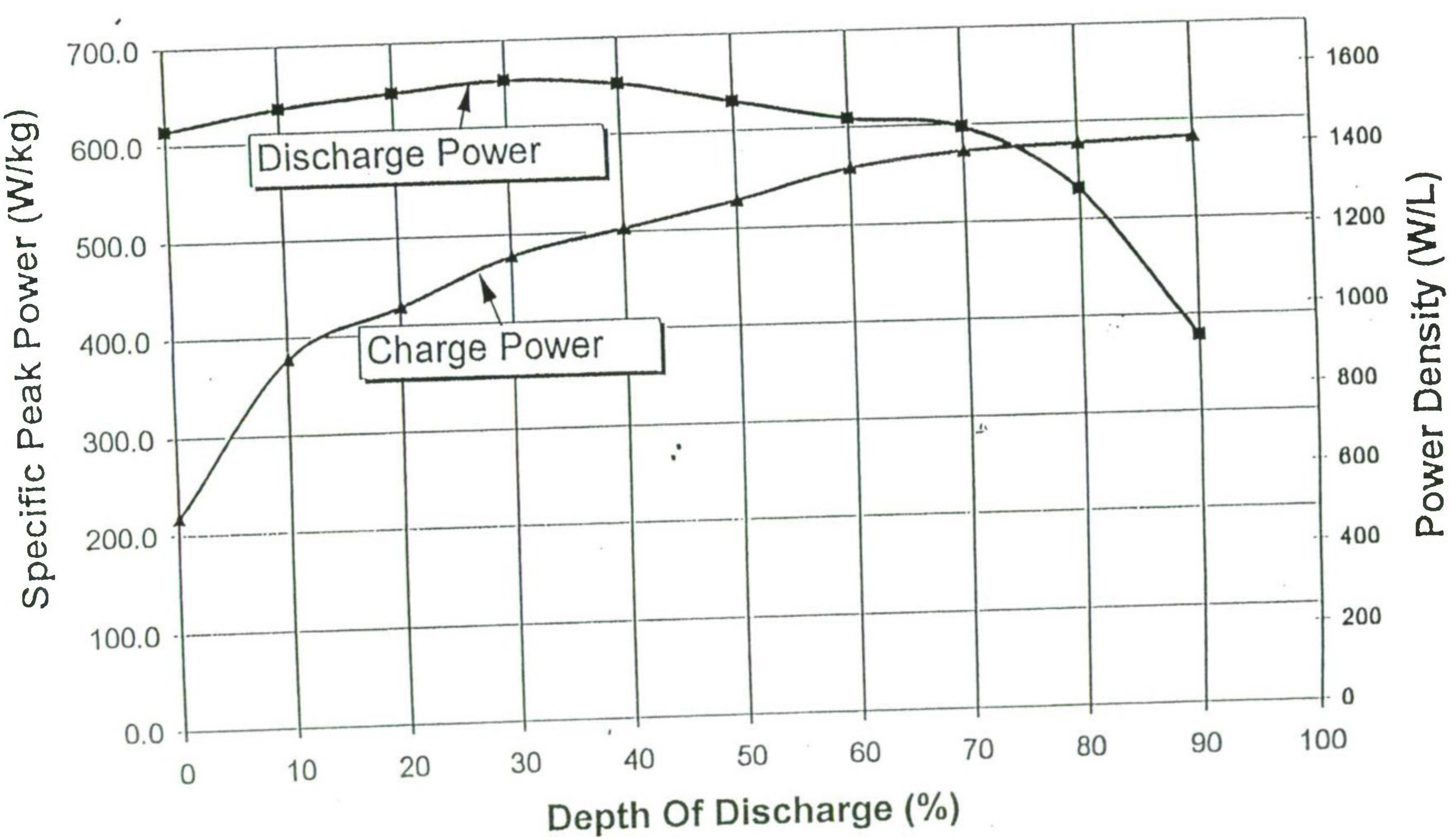
L = 240 mm
W = 102 mm
H = 81 mm

12-HEV-20
10 cells
20 Ah at 12 V

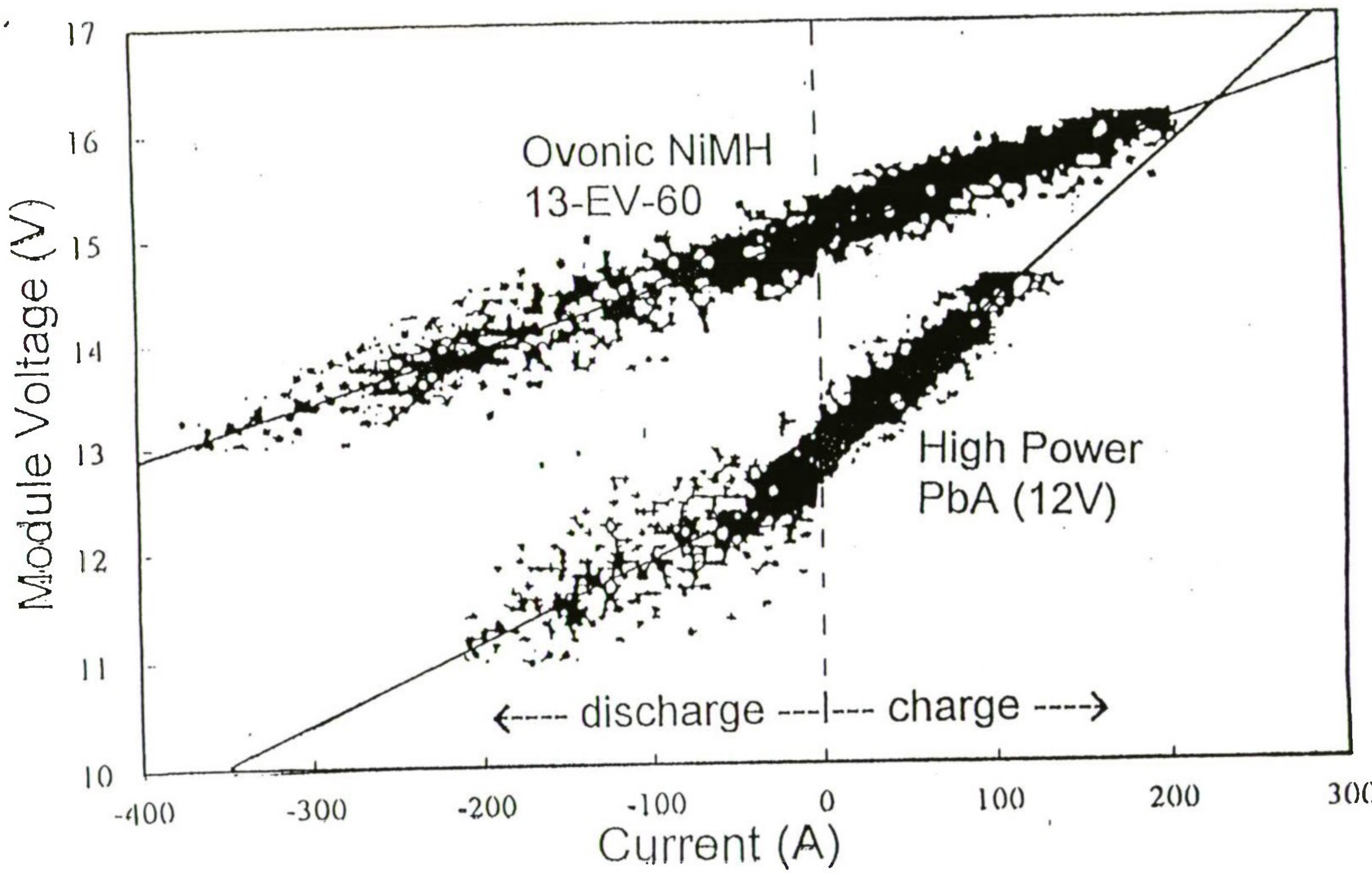


L = 340 mm
W = 102 mm
H = 91 mm

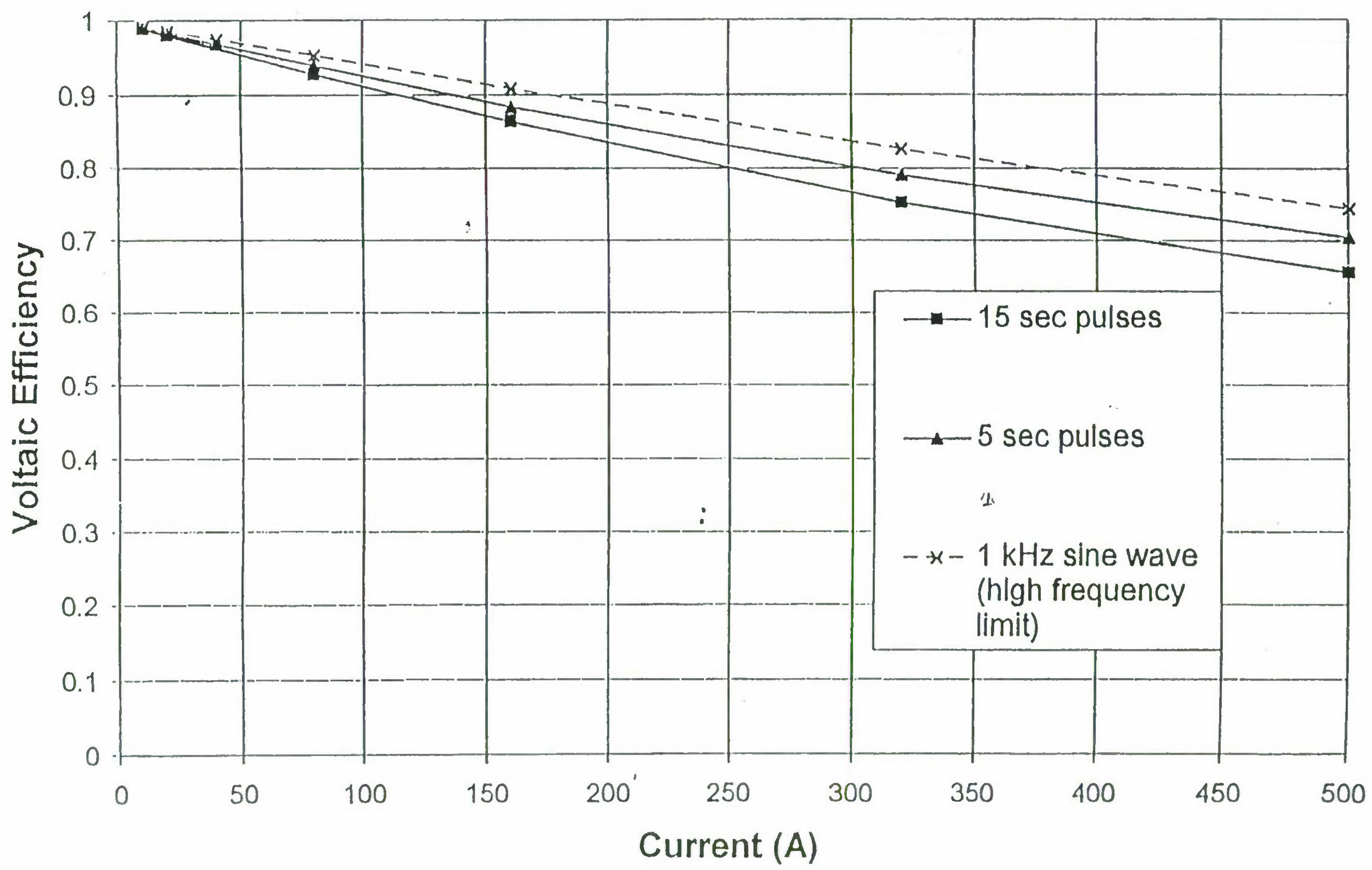
Ovonic 13HEV60 Module Power Performance Dependence on Depth of Discharge



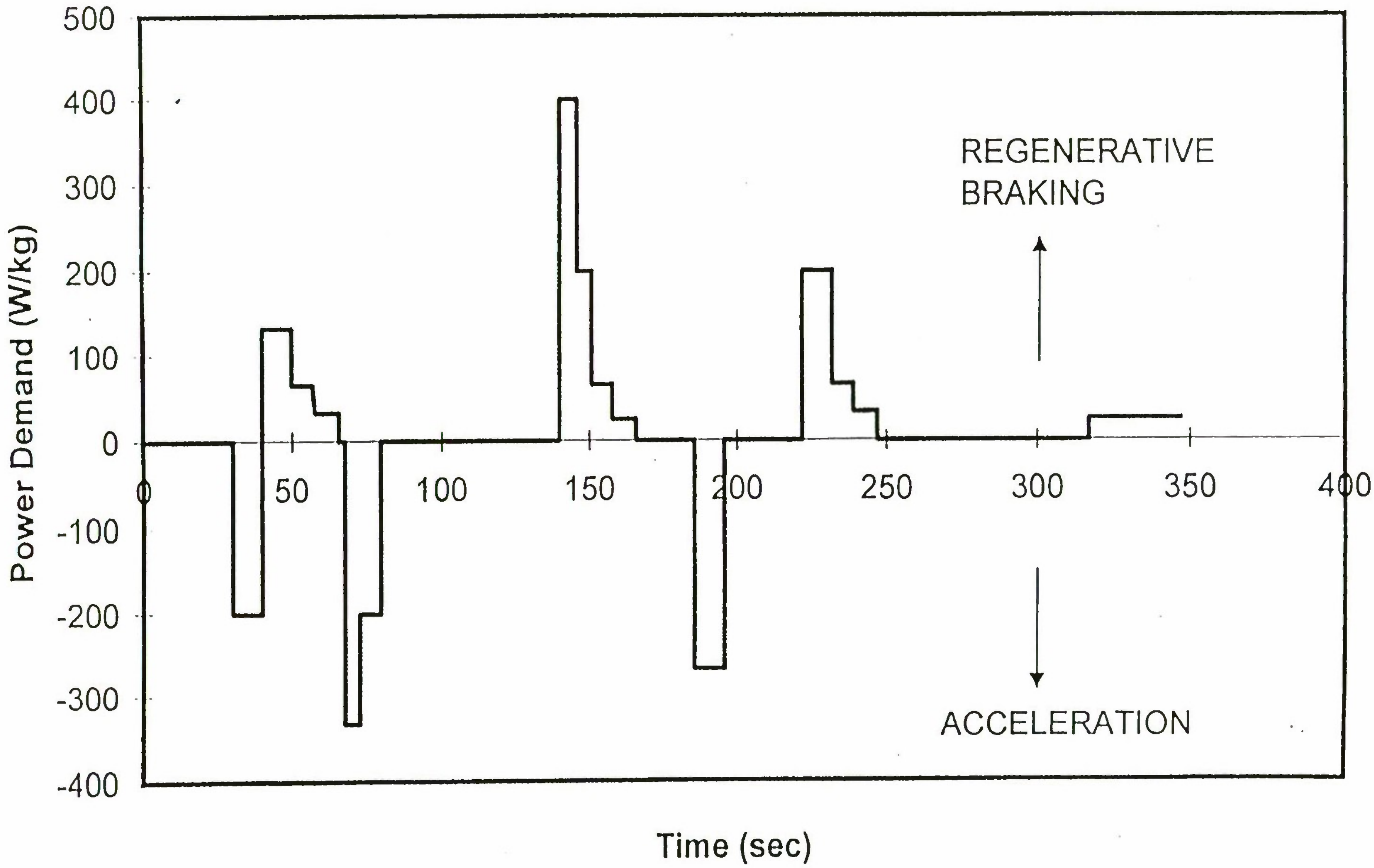
V-I PLOT FOR AGGRESSIVE DRIVING CYCLE



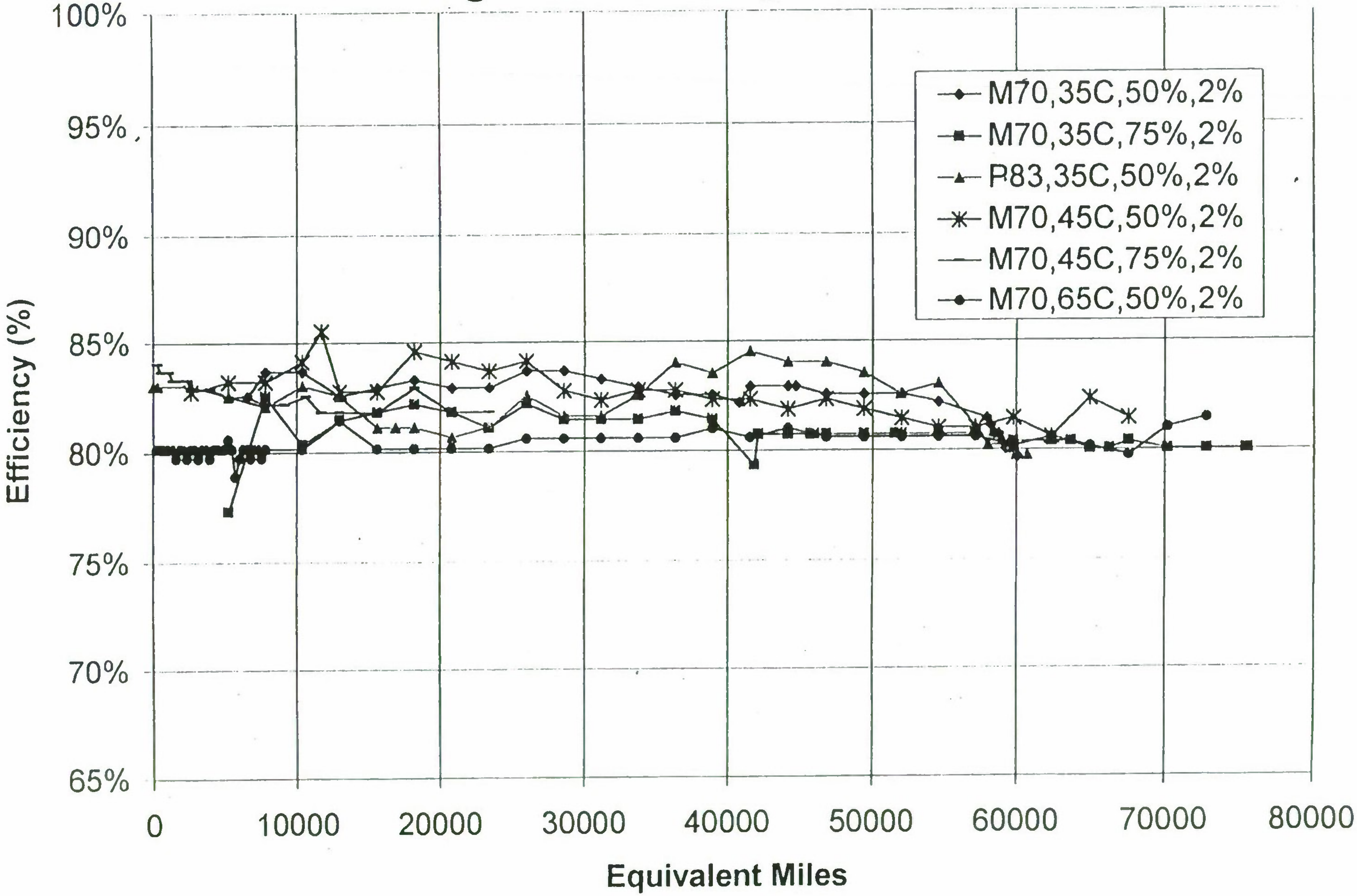
Ovonic HEV-60 Battery Voltaic Efficiency



Ovonic Simplified HEV Charge Sustaining Cycle



Energy Efficiency During HEV Life Cycle Tests



PERFORMANCE ADVANTAGES FOR HEV MODE

1. Cycle Life

    - improved cycle life with shallow cycles
    - improved cycle life with no overcharge

2. Efficiency

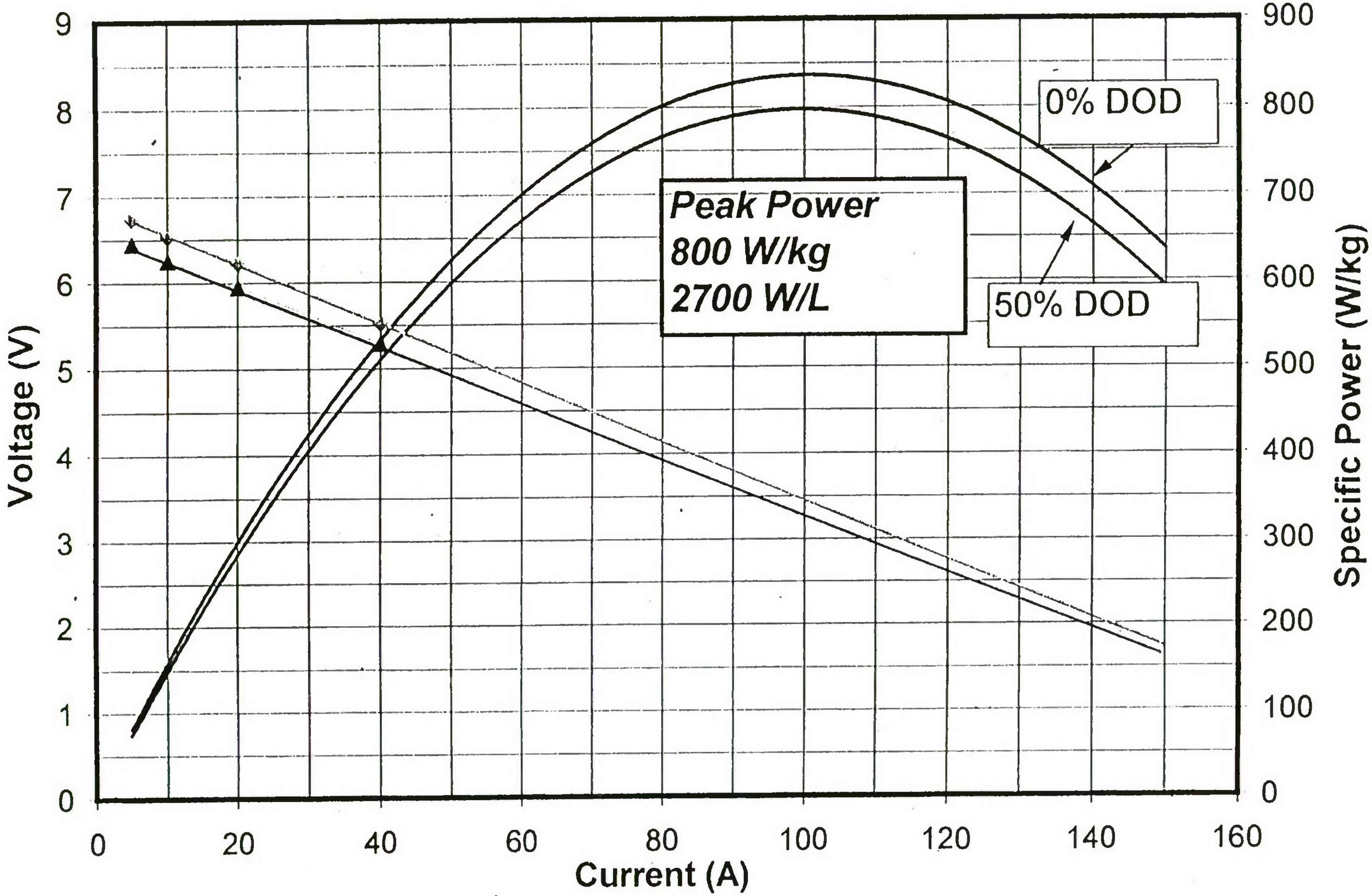
    - ~100% coulombic efficiency
    - high efficiencies to >60C

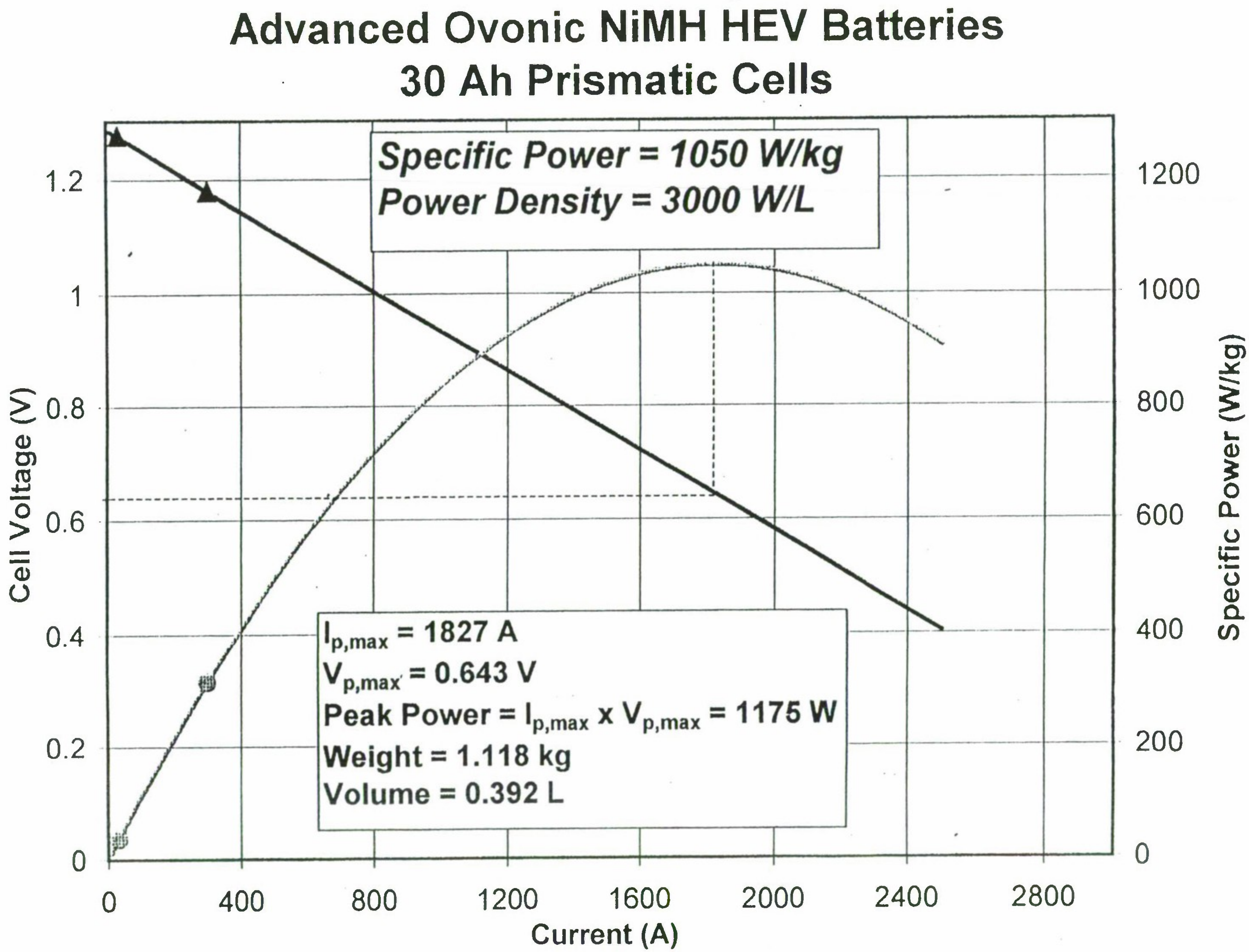
HYBRID ELECTRIC VEHICLE DEMONSTRATIONS OF OVONIC NICKEL-METAL HYDRIDE BATTERIES

1995 PNGV FutureCar Challenge	California State Univ., Chico Converted Saturn (2nd Place)
1996 PNGV FutureCar Challenge	Lawrence Tech University Converted Ford Taurus (2nd Place)
1997 PNGV FutureCar	Univ. of California, Davis Converted Ford Taurus (1st Place, >60 mpg hwy)
1998 Detroit Auto Show	GM Show Vehicles - GM Series HEV - GM Parallel HEV - GM Fuel Cell HEV
1998 Paris Auto Show	Opel Fuel Cell HEV
1999 Detroit Auto Show	DaimlerChrysler Jeep Commander Fuel Cell HEV

HIGH POWER OVONIC NiMH CYLINDRICAL CELLS

6-V Module of 5 C-Cells: Capacity = 3.5 Ah





Advanced Ovonic NiMH HEV Batteries
30 Ah Prismatic Cells
Specific Power = 1050 W/kg
Power Density = 3000 W/L
$I_{p,max}$ = 1827 A
$V_{p,max}$ = 0.643 V
Peak Power = $I_{p,max}$ x $V_{p,max}$ = 1175 W
Weight = 1.118 kg
Volume = 0.392 L
Cell Voltage (V)
Specific Power (W/kg)
Current (A)
0
0.2
0.4
0.6
0.8
1
1.2
200
400
600
800
1000
1200
2400
2800

SUMMARY AND CONCLUSIONS

Ovonic NiMH HEV Batteries Available at 15, 20, 28, 60 Ah

Peak Power and Regen Power Over 500 W/kg and 1200 W/L

Excellent Energy Efficiency up to 60C

HEV Mode Cycle Life Approaches 100,000 Miles Equivalent

Demonstrated in HEV Mode Operation
in Modules, Full Packs, and Vehicles

Over 1000 W/kg and 3000 W/L Power in Prototype Cells

BOLDER TECHNOLOGIES CORPORATION

Application of Thin Metal Film (*TMF*®) Technology for Hybrid Electric Vehicles

by

Arnold Allen

BOLDER Technologies Corporation

303-215-7230

arnie.allen@boldertmf.com

Presented at

1999 Vehicle Technologies Alternative Propulsion Symposium

Sponsored by: TACOM-TARDEC

May 4, 1999

Topics Covered

- Introduction
  - *BOLDER* Technologies Corporation
  - Cell design and size
  - Cell attributes
- Comparison to other battery technologies
- Ultrafast Response
- HEV Concepts and Requirements
- Voltage vs. State of Charge
- Conclusions

BOLDER TECHNOLOGIES CORPORATION

Corporate Background

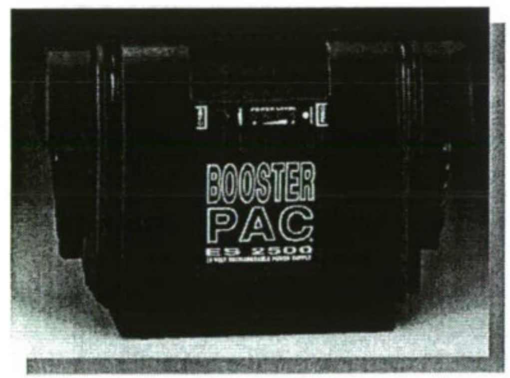
- Founded 1991
- Innovative design based on well established electrochemistry
- Protected by patents and trade secrets
- Wide sampling, limited commercial shipments
- IPO 5/1/96, NASDAQ "BOLD"
- 1st high volume production line, operational 9/97
- Commercial production announced - 9/98
- First Qtr '99 announced two battery products
  - REBEL
  - Jump Start

BOLDER TECHNOLOGIES CORPORATION

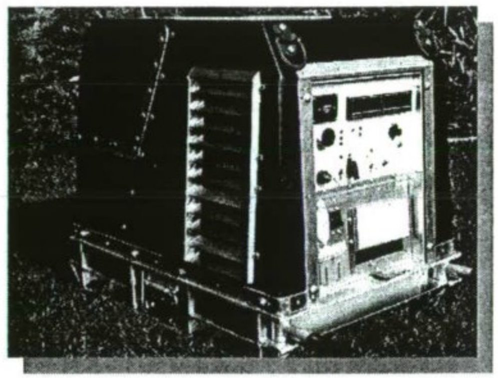
BOLDER TECHNOLOGIES CORPORATION

The Power of Enabling Technology

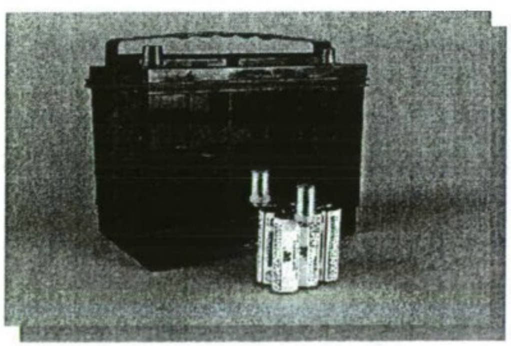
Market Opportunities



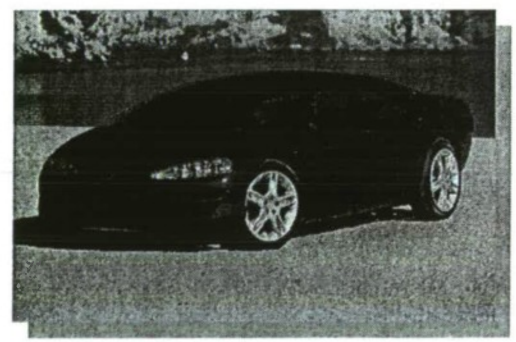
Emergency Starting Unit


Goodman - Ball
Field Generator

Portable Tools

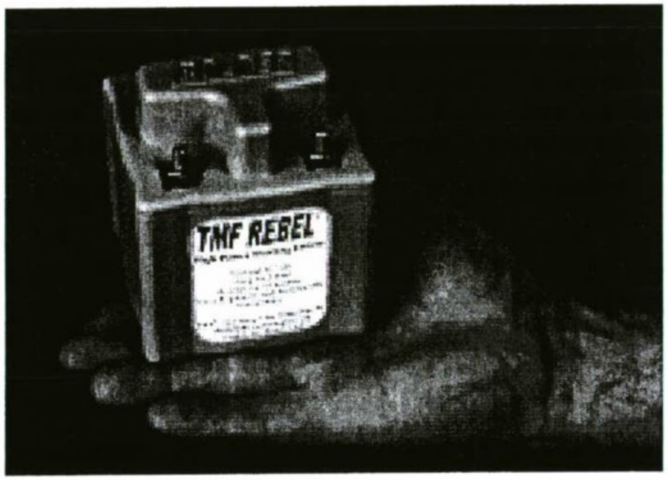

Car Starting


Electronics &
Telecom


Hybrid Vehicles

BOLDER TECHNOLOGIES CORPORATION

TMF Technology



More power per pound than any other battery!

Peak Short Circuit Current >1200 Amps

1 amp-hour capacity

300 Peak starting amps

1.6 LB.

Light weight	-	Easy to transport!
High power	-	Efficient engine starting!
Fast charging	-	Ready to go!
Versatile	-	Use for primary starting or emergency starting!

BOLDER TECHNOLOGIES CORPORATION

5 Ah Cell SBIR Development Program

Program Goal: Development of 5 Ah Thin Metal Film (TMF) Lead Acid cells for High Power Electric (Pulse Power) or Hybrid Vehicles.

Control No.: DAAH01-96-C-R139

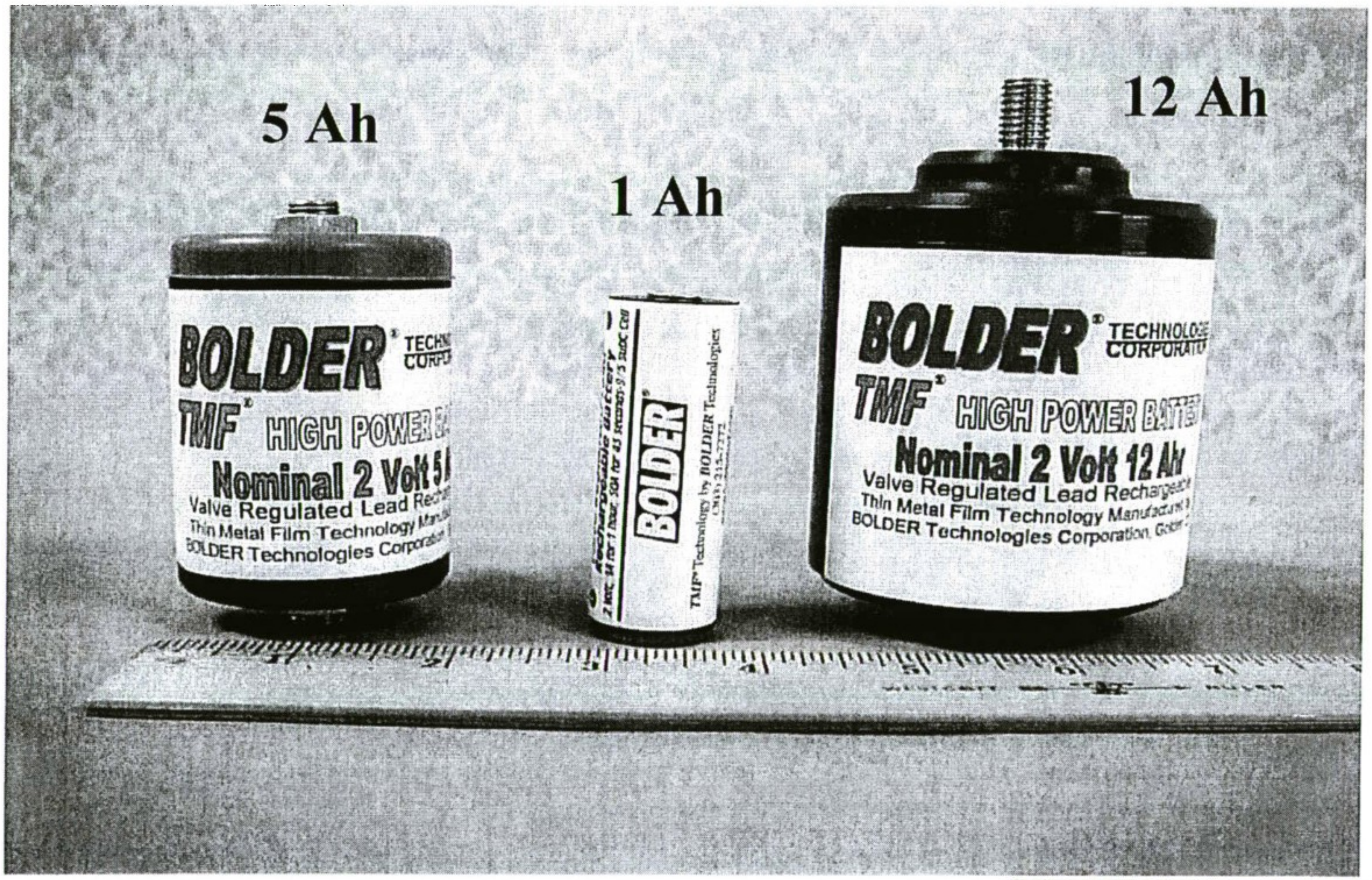
Final Report Submitted: 15 Feb 1999

Results:

1. Successful scaling up of size from 1 to 5 Ah.
2. Specific Power and Specific energy unattainable by any other commercially available battery technology was demonstrated >6Wh/kg at 2000 W/kg.
3. Excellent resistance to shock and vibration.
4. Superior self-discharge rates to nickel oxide based battery systems.
5. Charge efficiency of:
   a. 86-90% on cycle testing
   b. Up to 94% on a pulse discharge test

BOLDER TECHNOLOGIES Corporation

Scalability of *TMF*® Technology



BOLDER TECHNOLOGIES CORPORATION

The Highest Power Available

Low Cost

Fast Recharge

Stable Voltage

TMF

No Memory

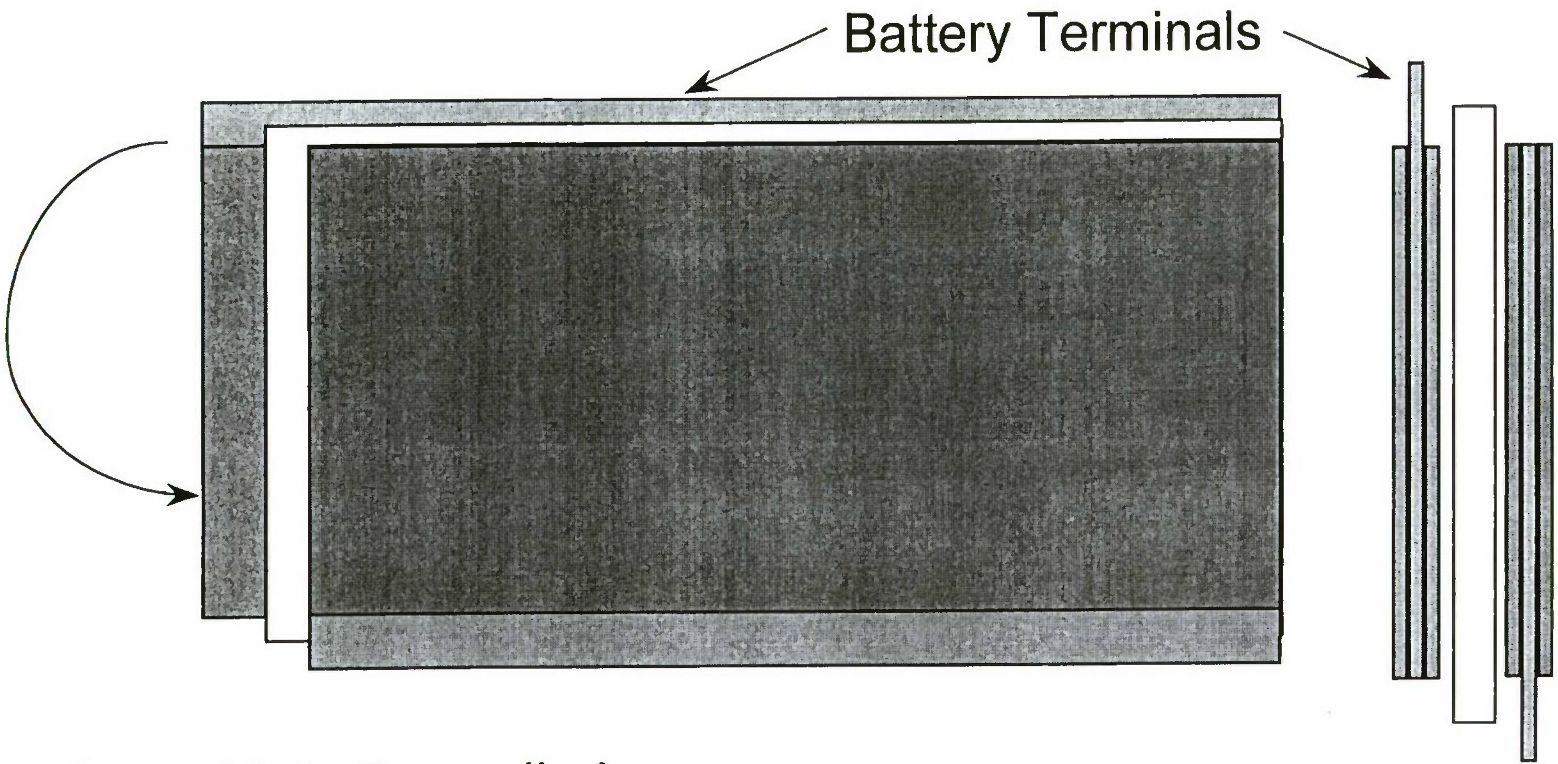
Cool Operation

Small Size

Good Low Temperature Specs

Easy to Recycle

BOLDER Wound Element Construction



Assembly is then rolled.

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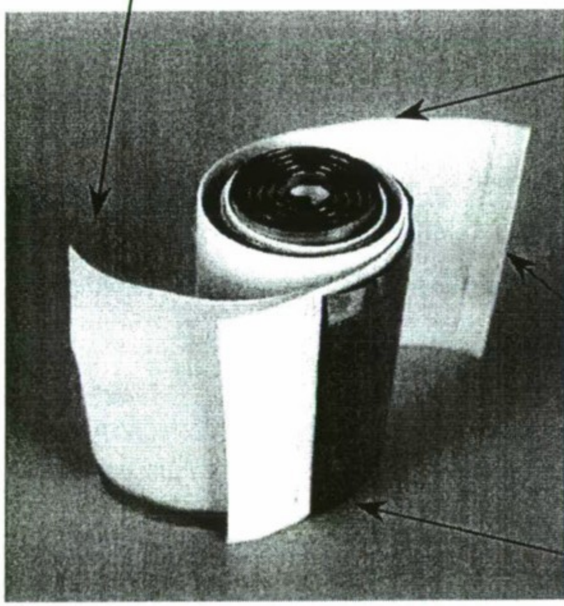
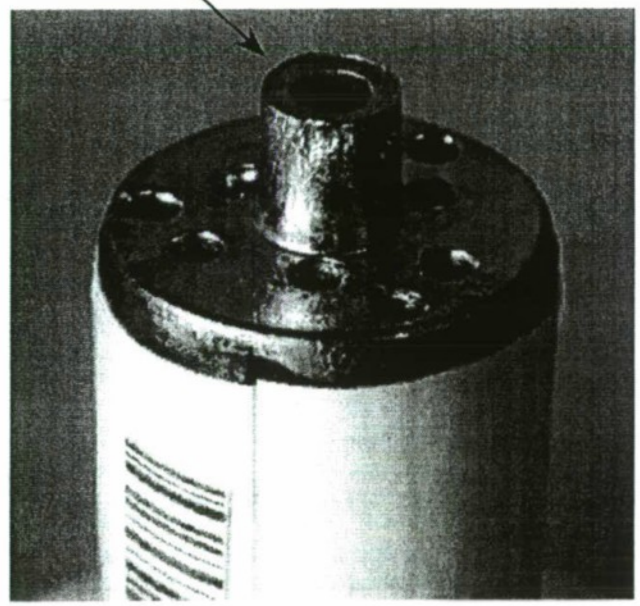
TMF Cell Design





- 16 X the surface area of a car battery per unit of volume
- 1/80 the path length of a car battery

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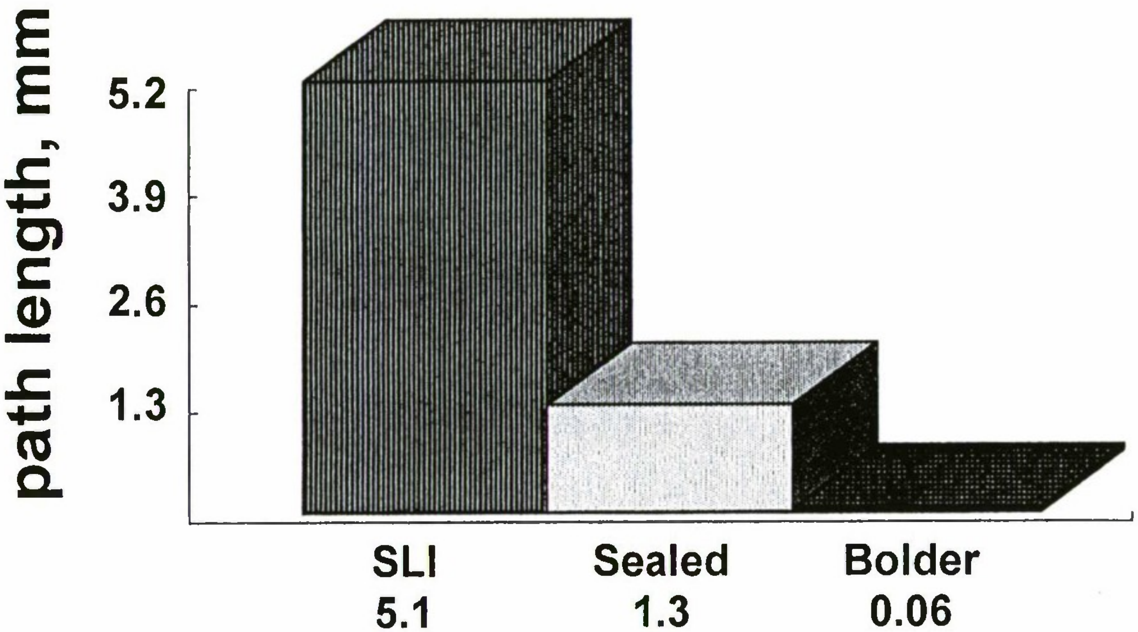
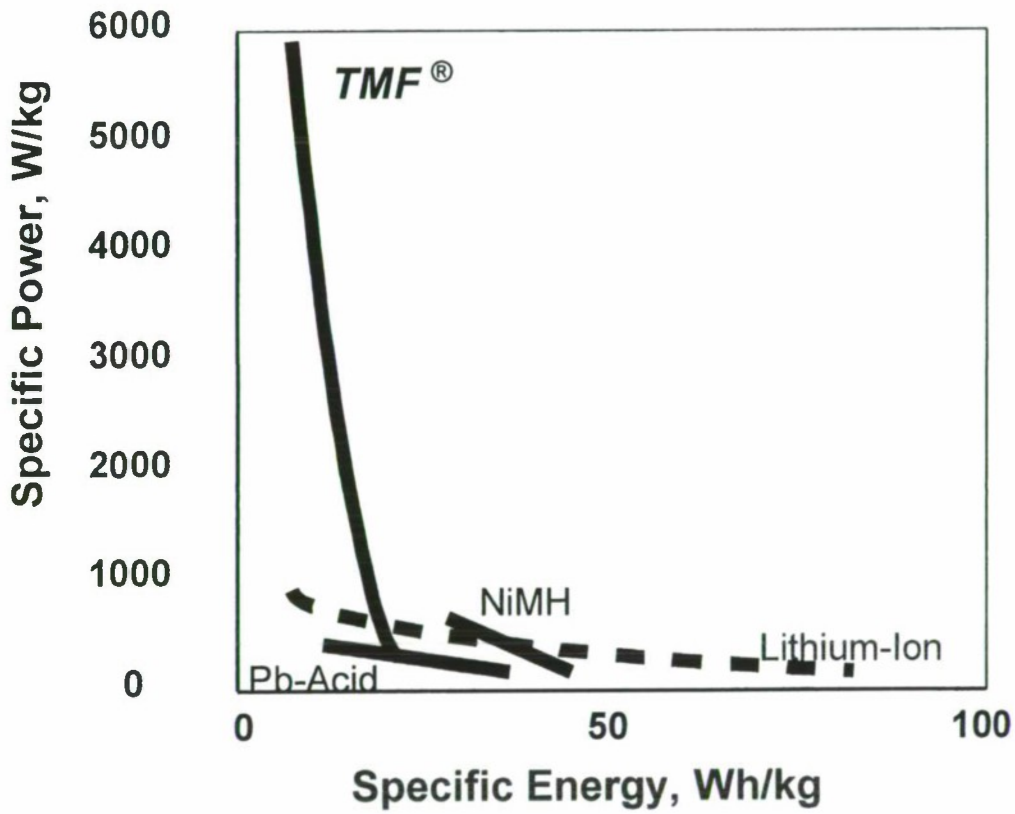
Design Comparisons



maximum path length through active material

BOLDER TECHNOLOGIES CORPORATION

Comparison of Power and Energy



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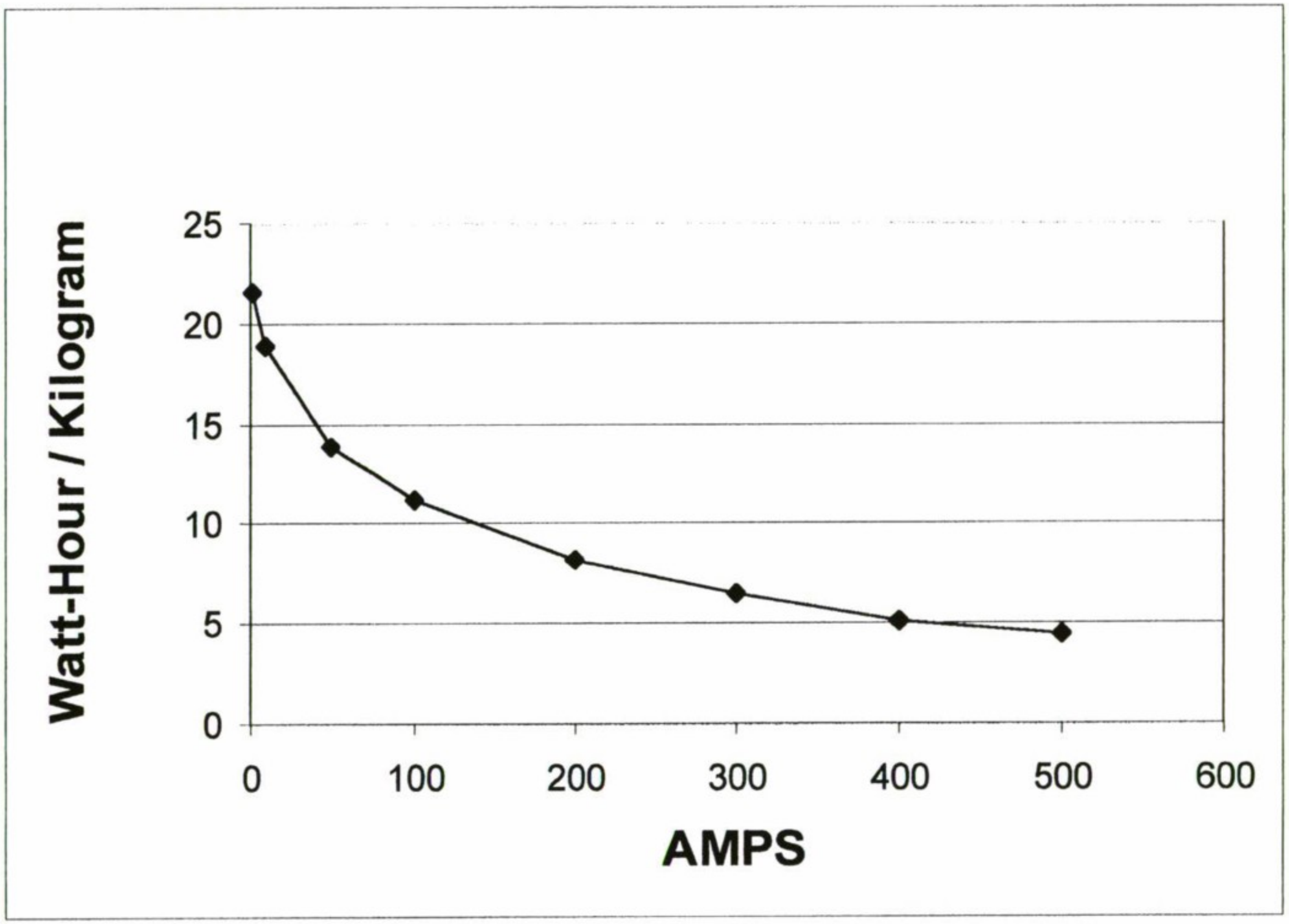
Watt-Hour / Kilogram vs. Current TMF 1Ah Cell



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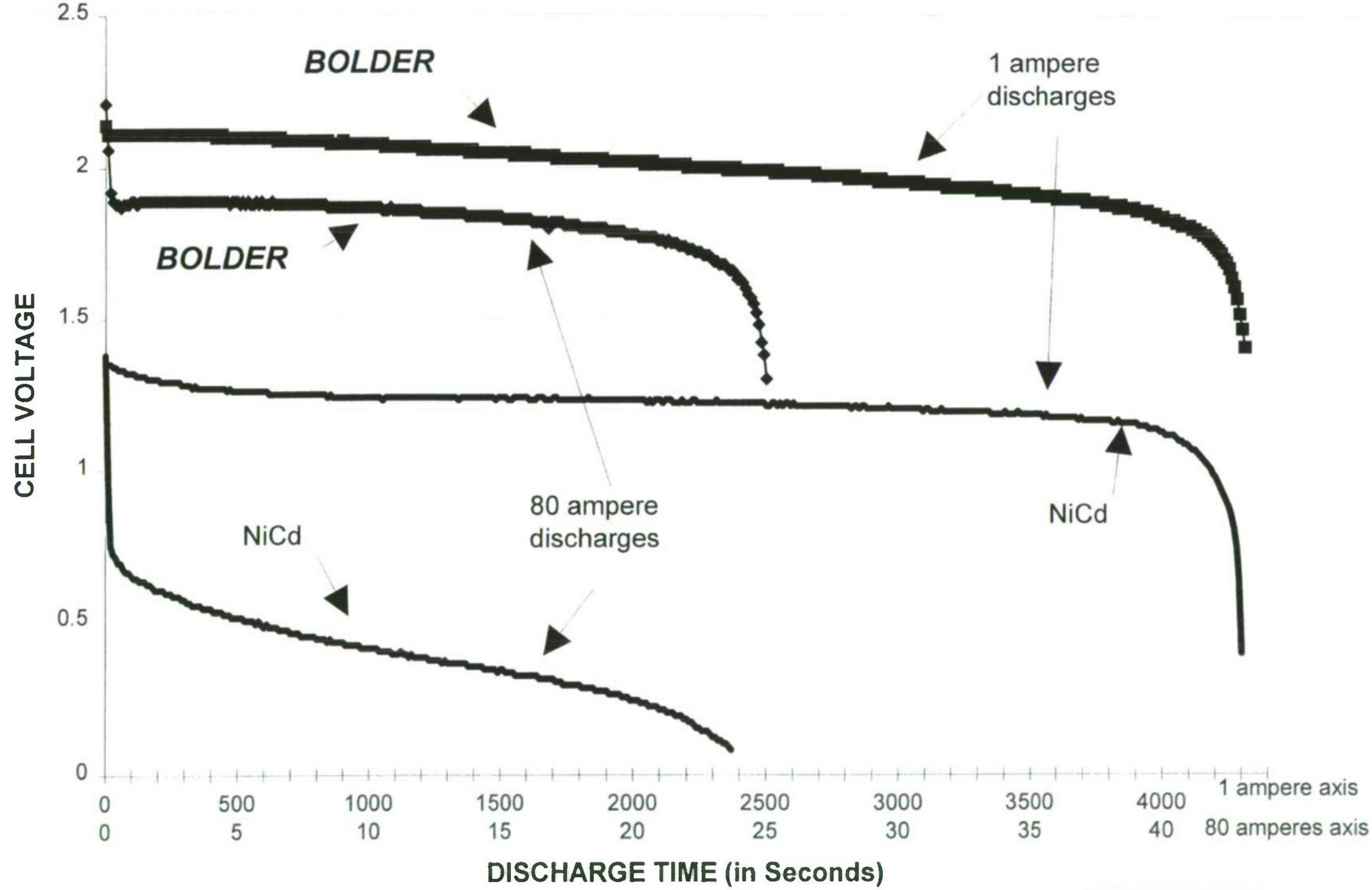
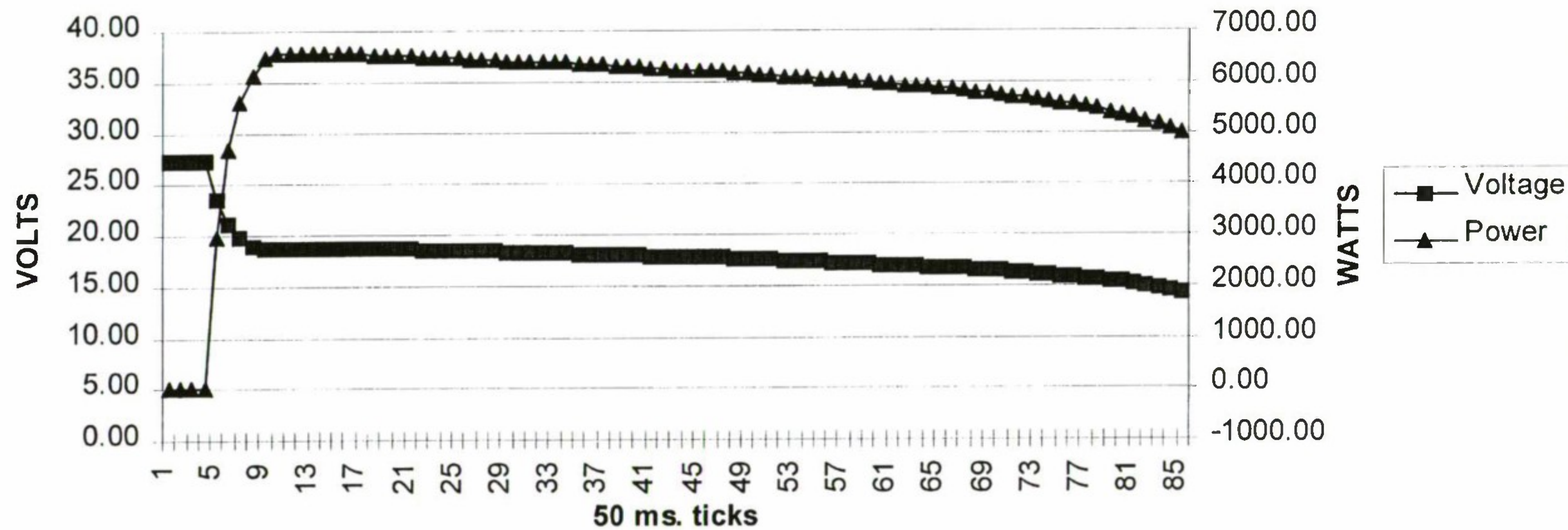
BOLDER 1.0Ah vs. NiCd 1.3 Ah at 80A AND 1A



BOLDER TECHNOLOGIES CORPORATION

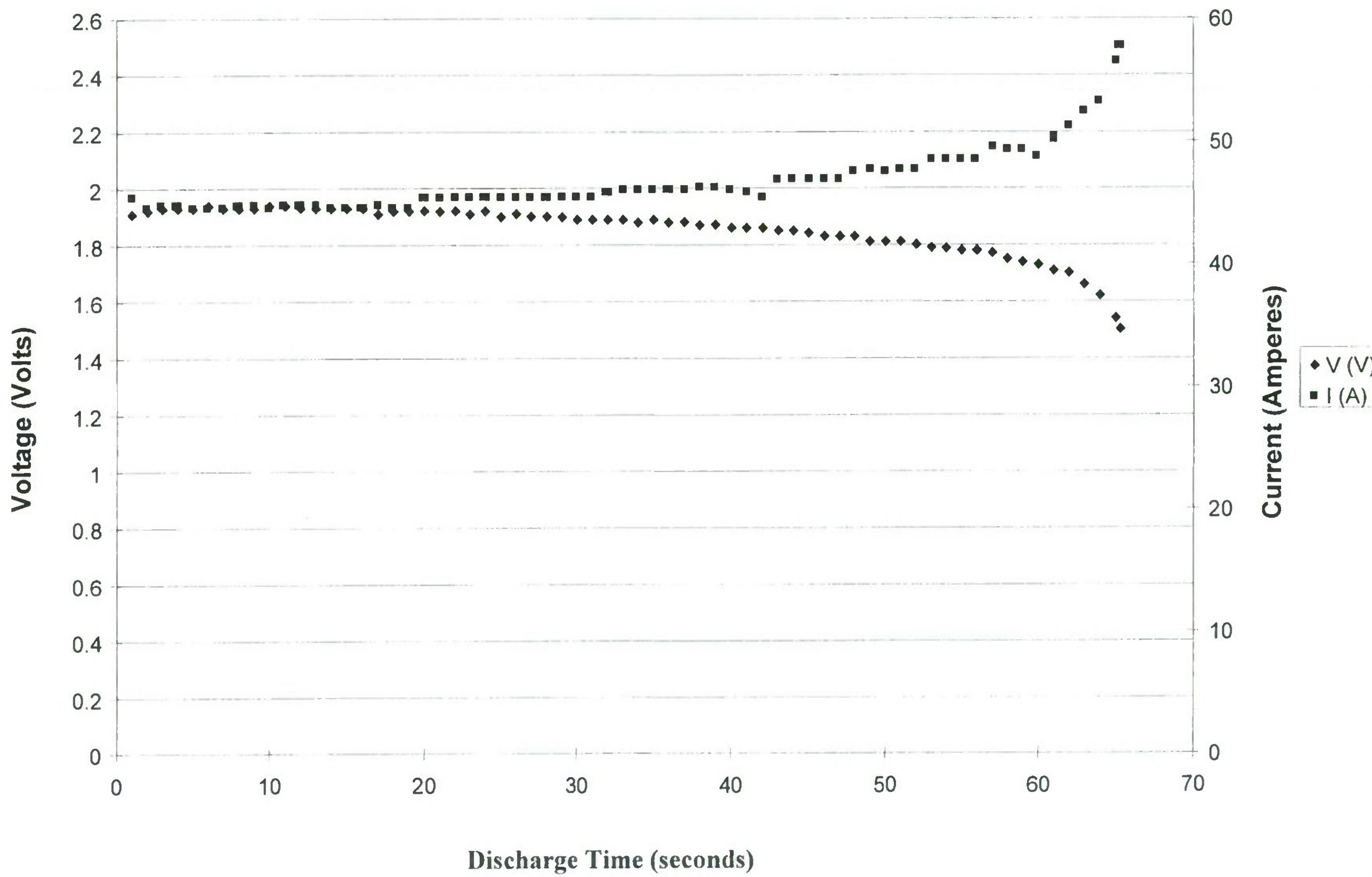
24 Volt Power @ 350 Amps

350 Amp Constant current discharge vs. time
(24 Volt 1Ah BOLDER Battery)
Total energy = 24,100.5 watt-seconds;
Total capacity expended = 1487.5 amp-seconds (.41C).
Total discharge time = 4.118 secs.
9/9/98



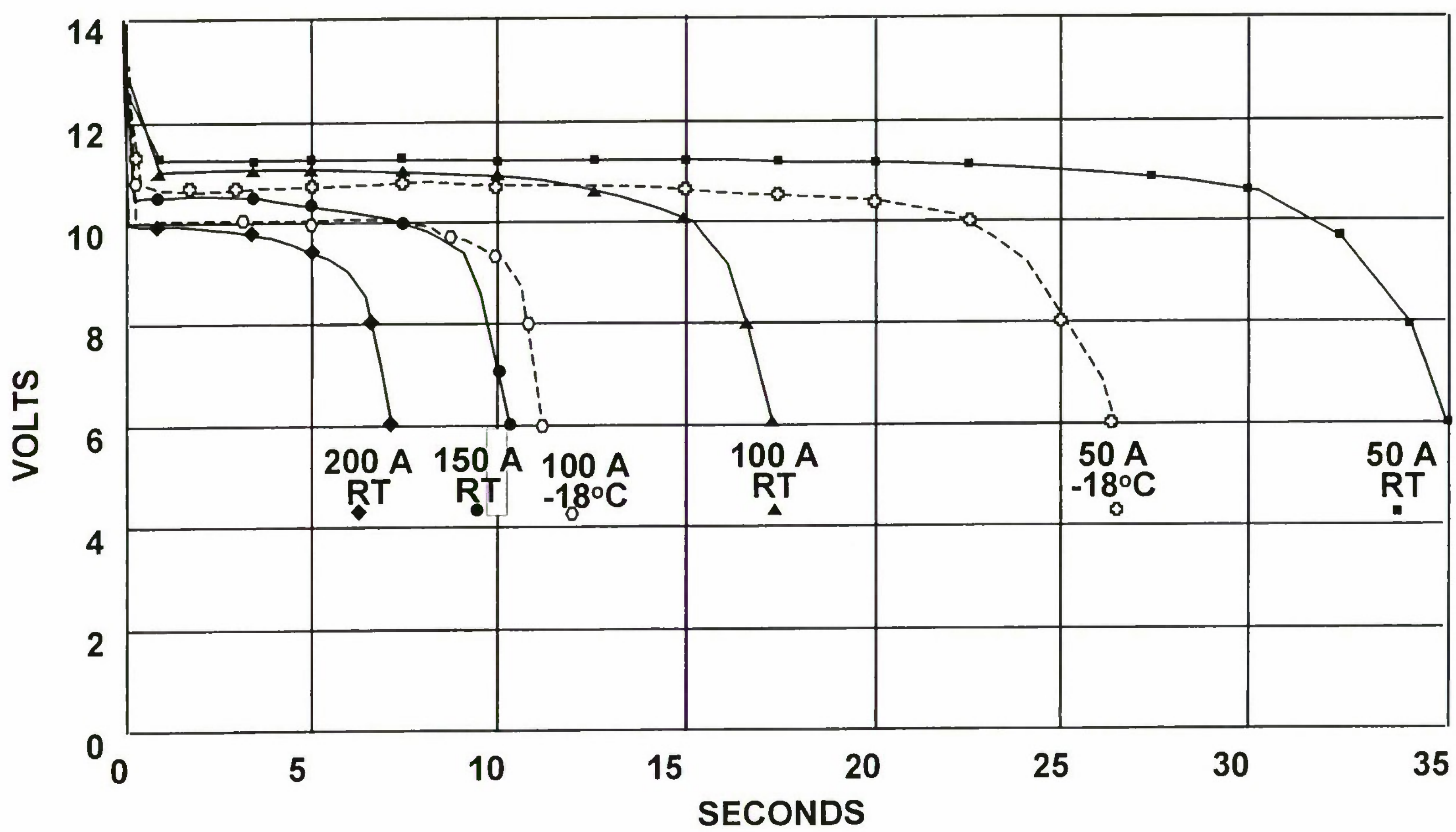
BOLDER TECHNOLOGIES

86 Watt Constant Power Test for UPS #450-100



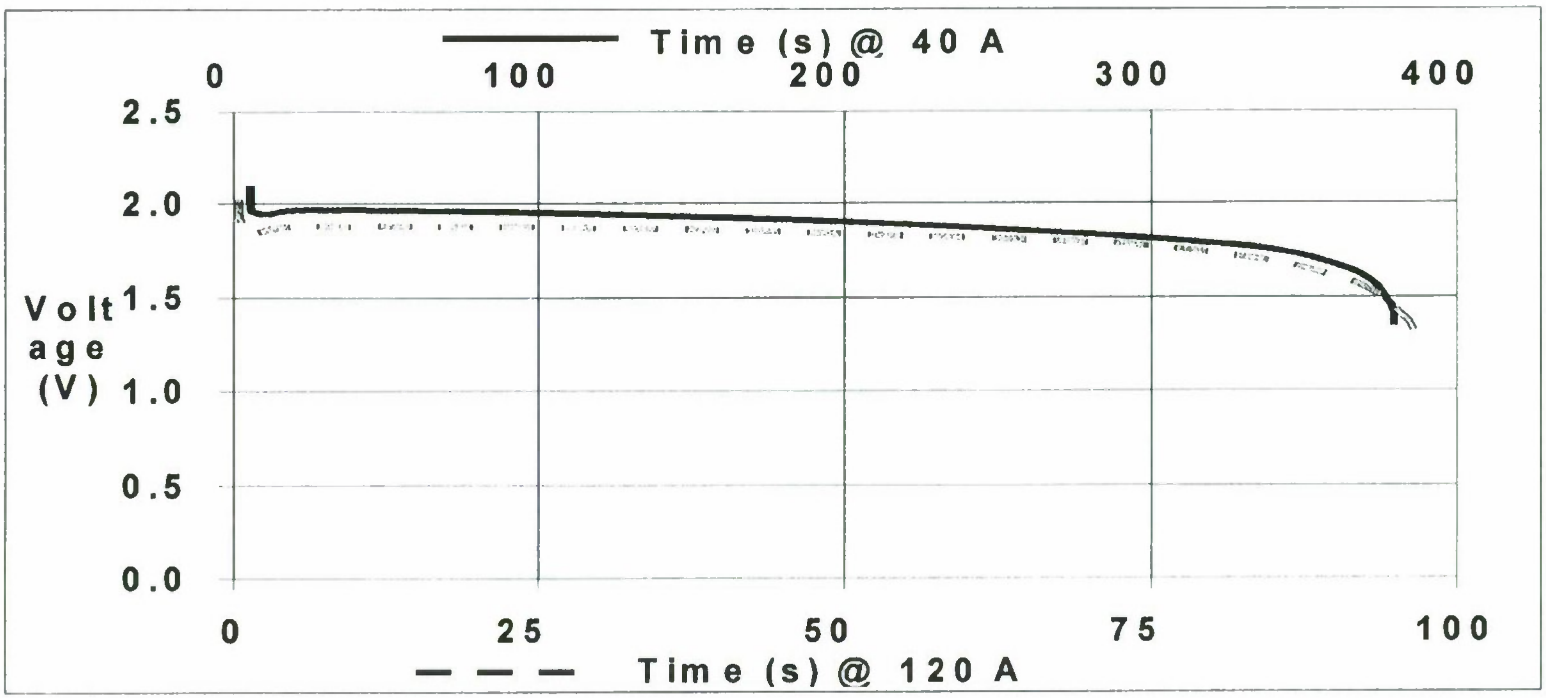
BOLDER TECHNOLOGIES CORPORATION

Discharge Time Under Load
12 volt, 1.0 Ampere Hour Battery



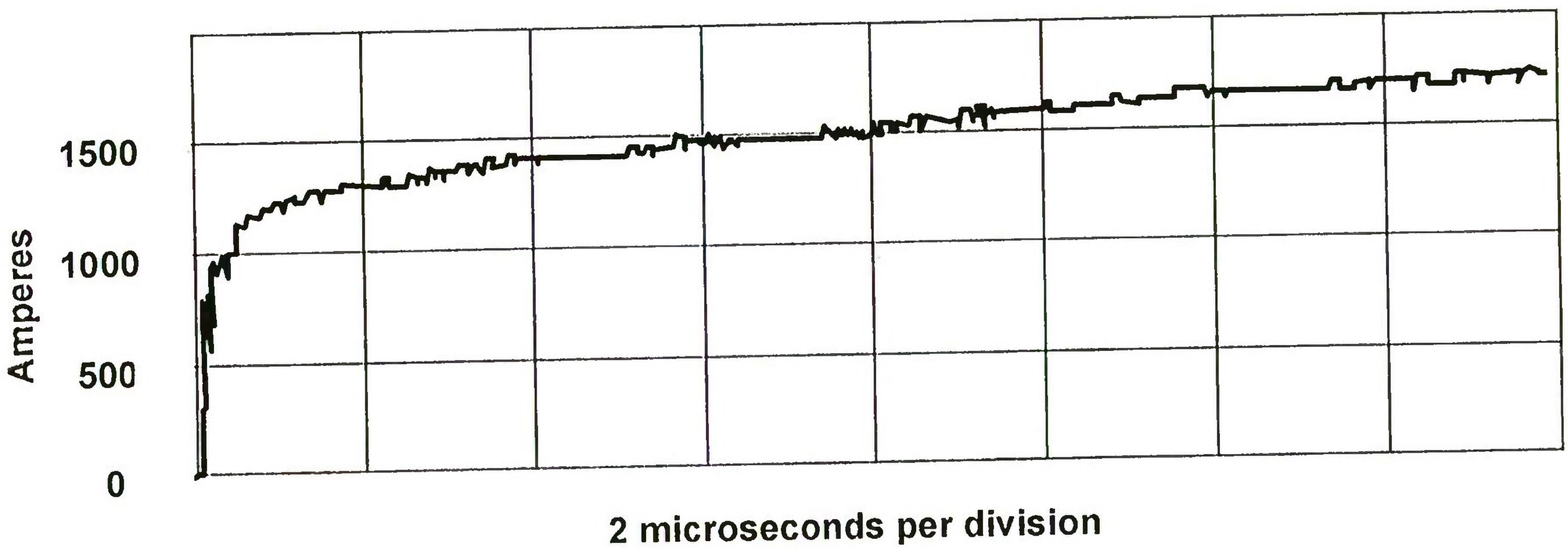
BOLDER TECHNOLOGIES CORPORATION

40A & 120 A DISCHARGE FOR 5Ah TMF CELL



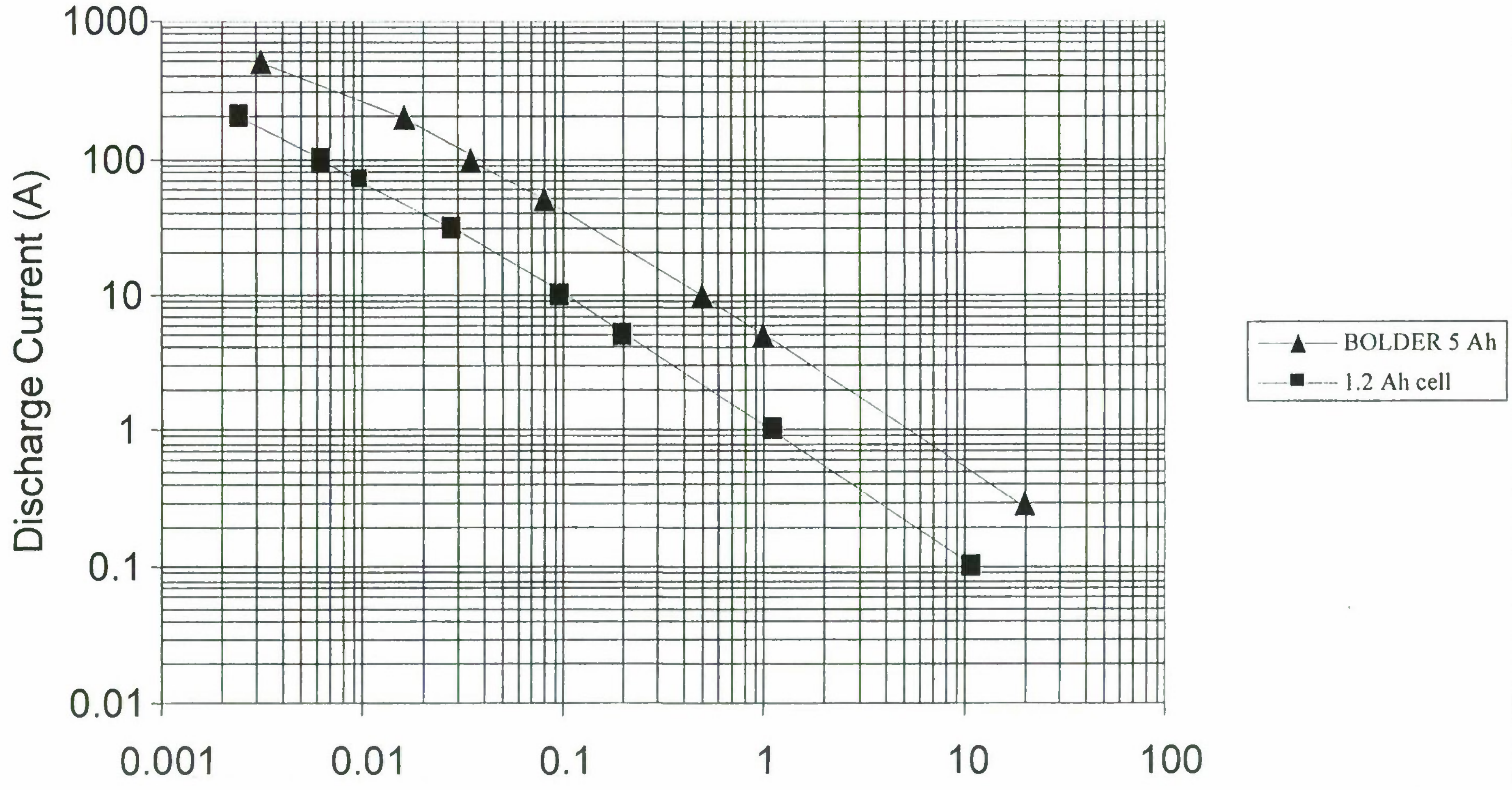
BOLDER TECHNOLOGIES CORPORATION

TMF 1.2 Ah Cell Peak Rate/Rise Time



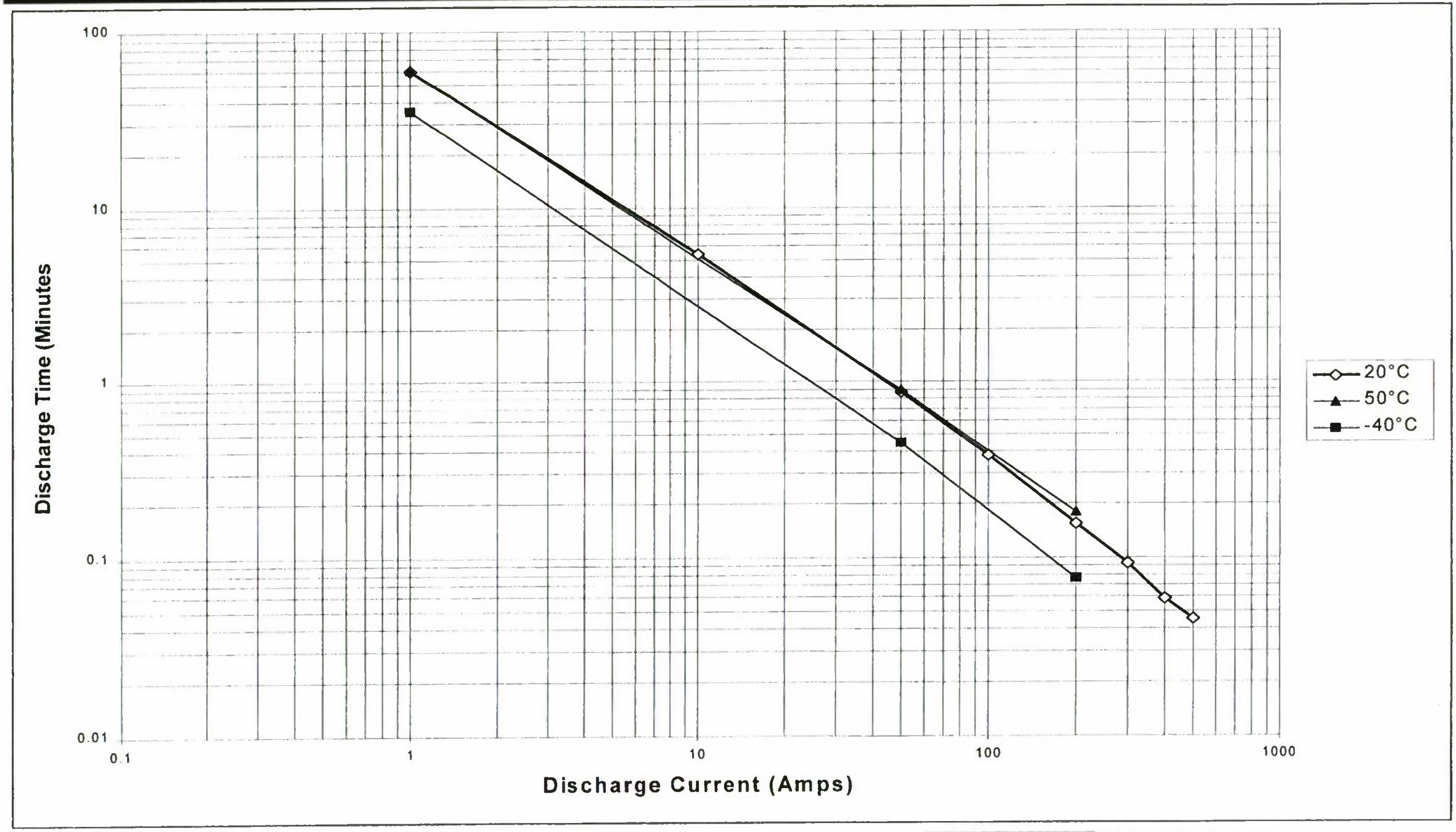
BOLDER TECHNOLOGIES CORPORATION

Peukert Plot Comparison of *BOLDER* 1.2 Ah and Prototype 5 Ah Cells



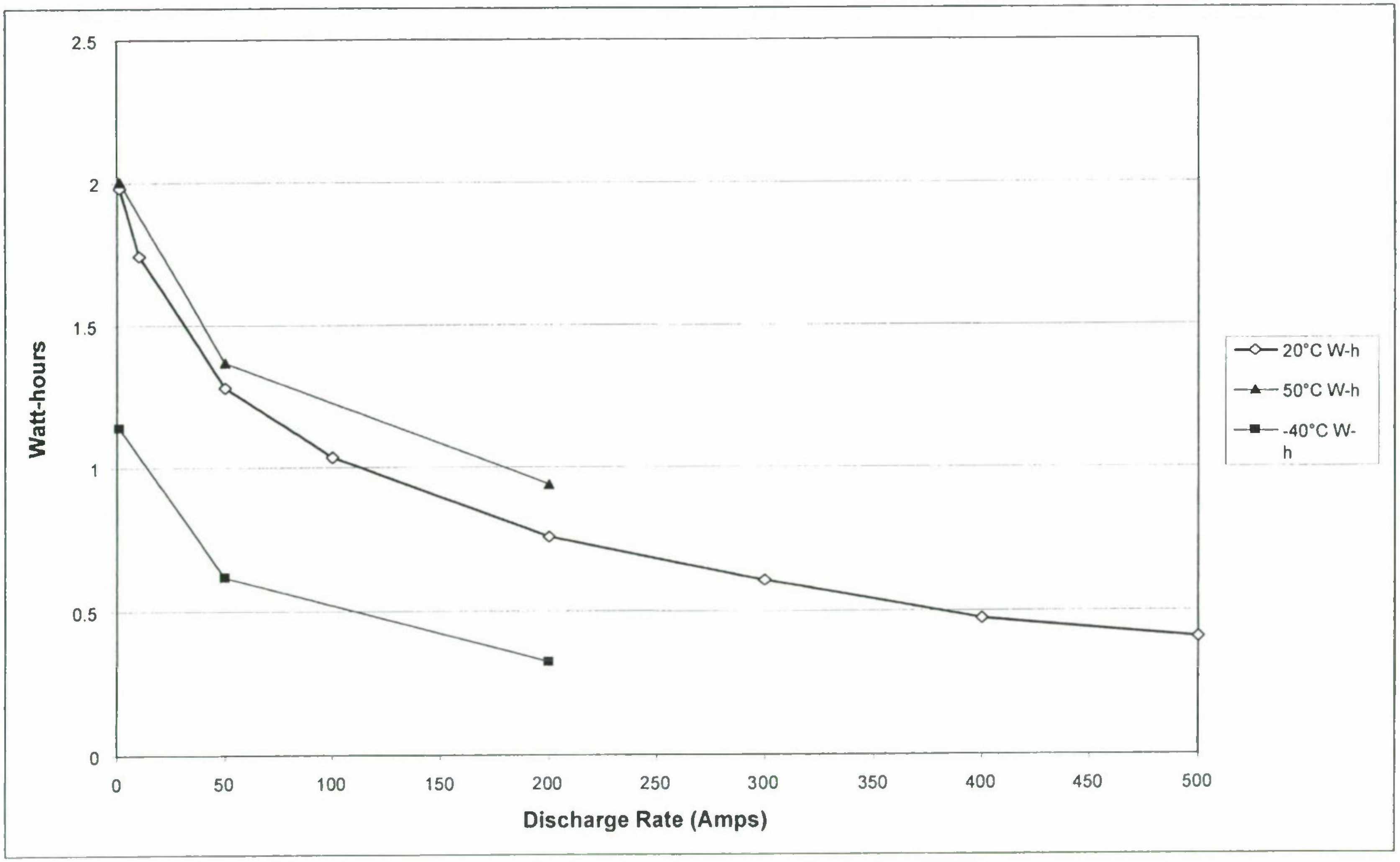
BOLDER TECHNOLOGIES CORPORATION

Peukert Curve
Discharge Current vs. Duration Time



BOLDER TECHNOLOGIES corporation

Watt-hours vs. Discharge Rate



BOLDER TECHNOLOGIES

Power and Energy Data for 1.0Ah *BOLDER* Cell

Constant Power Discharge	Watts W	Average Voltage V	Average Current A	Run Time sec.	Specific Power W/kg	Specific Energy Wh /kg
86W	86	1.85	47	60	1,049	17.5
44W	44	1.90	23.2	160	537	23.9
24W	24	1.95	12.3	300	293	24.4
14W	14	1.97	7.1	558	171	26.5
Constant Current Discharge						
270A	364	1.35	270	6.1	4,439	7.34
200A	300	1.5	200	9.1	3,659	9.2
100A	175	1.75	100	25	2,134	14.8
100A/-18°C	160	1.6	100	11.5	1,951	6.2
80A	144	1.8	80	25.2	1,756	12.3
50A/-18°C	86	1.72	50	26.5	1,049	7.7
1A	2	2.0	1	4400	24.4	29.8

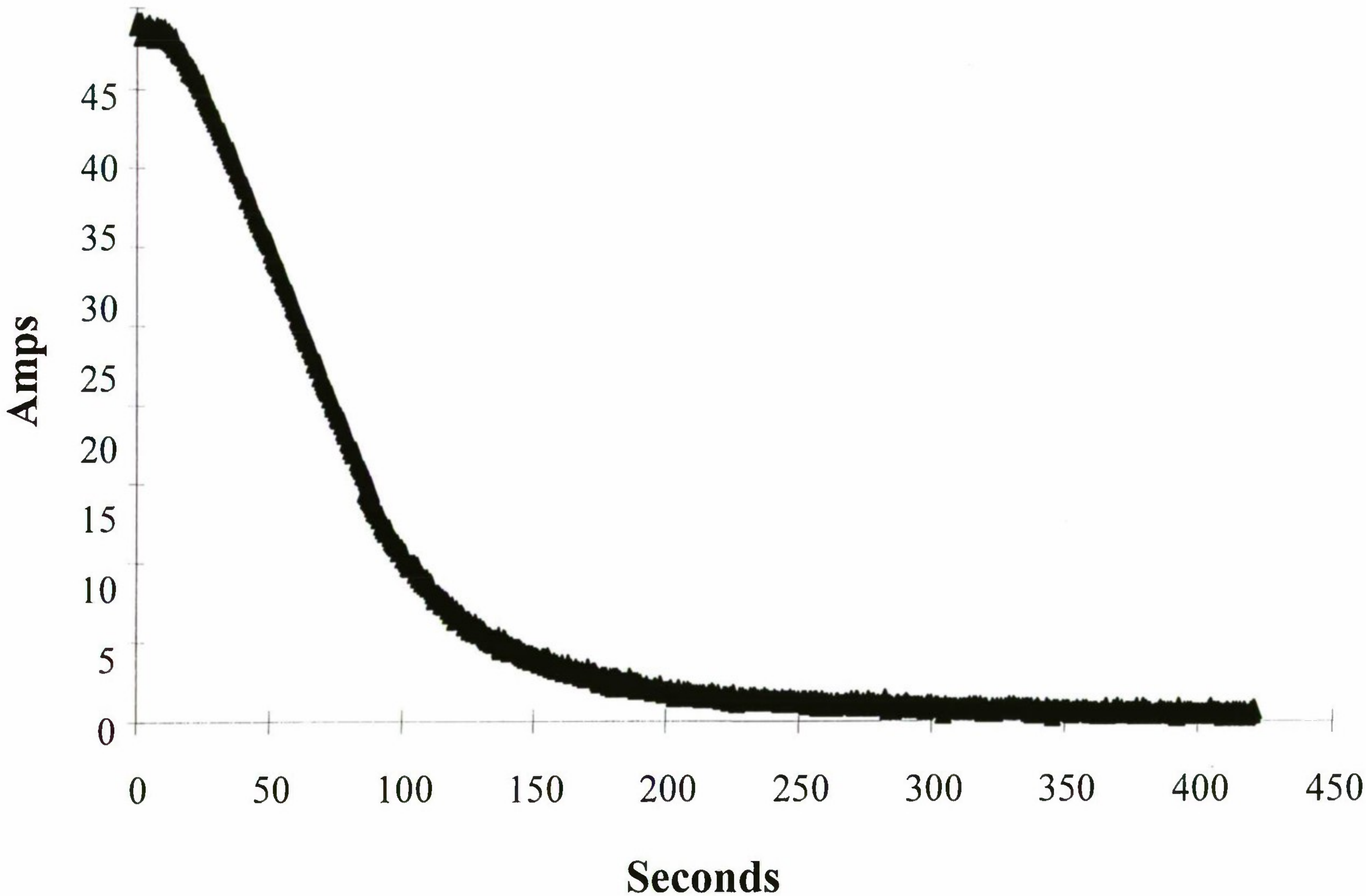
Power and Energy Density for 5Ah Cell

Constant Current Discharge	Watts W	Average Voltage V	Run Time Sec.	Specific Power W/kg	Specific Energy Wh/kg
1000 A*	1600	1.60	6	3478	5.80
500 A	900	1.80	11.5	1957	6.30
200 A	366	1.83	51	796	11.30
120 A	224	1.87	90	488	12.20
40 A	76	1.9	370	165	17.00
5 A	10	2.0	3600	22.0	21.70
0.250 A	0.50	2.0	83400	1.10	25.20

*** estimated value based on Peukert curve**

BOLDER TECHNOLOGIES CORPORATION

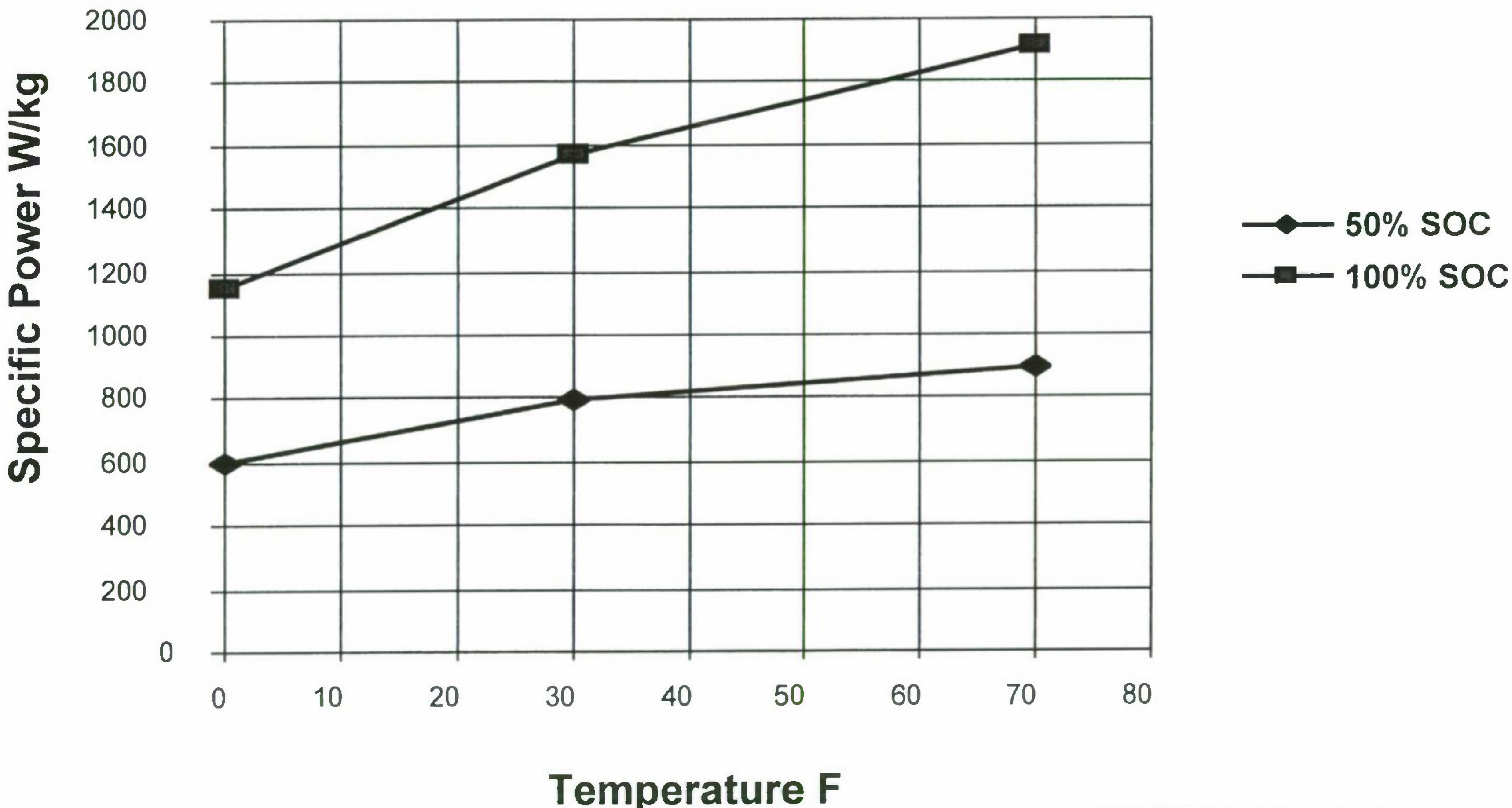
2.55 Volt Recharge Curve *TMF* Cell



BOLDER TECHNOLOGIES CORPORATION

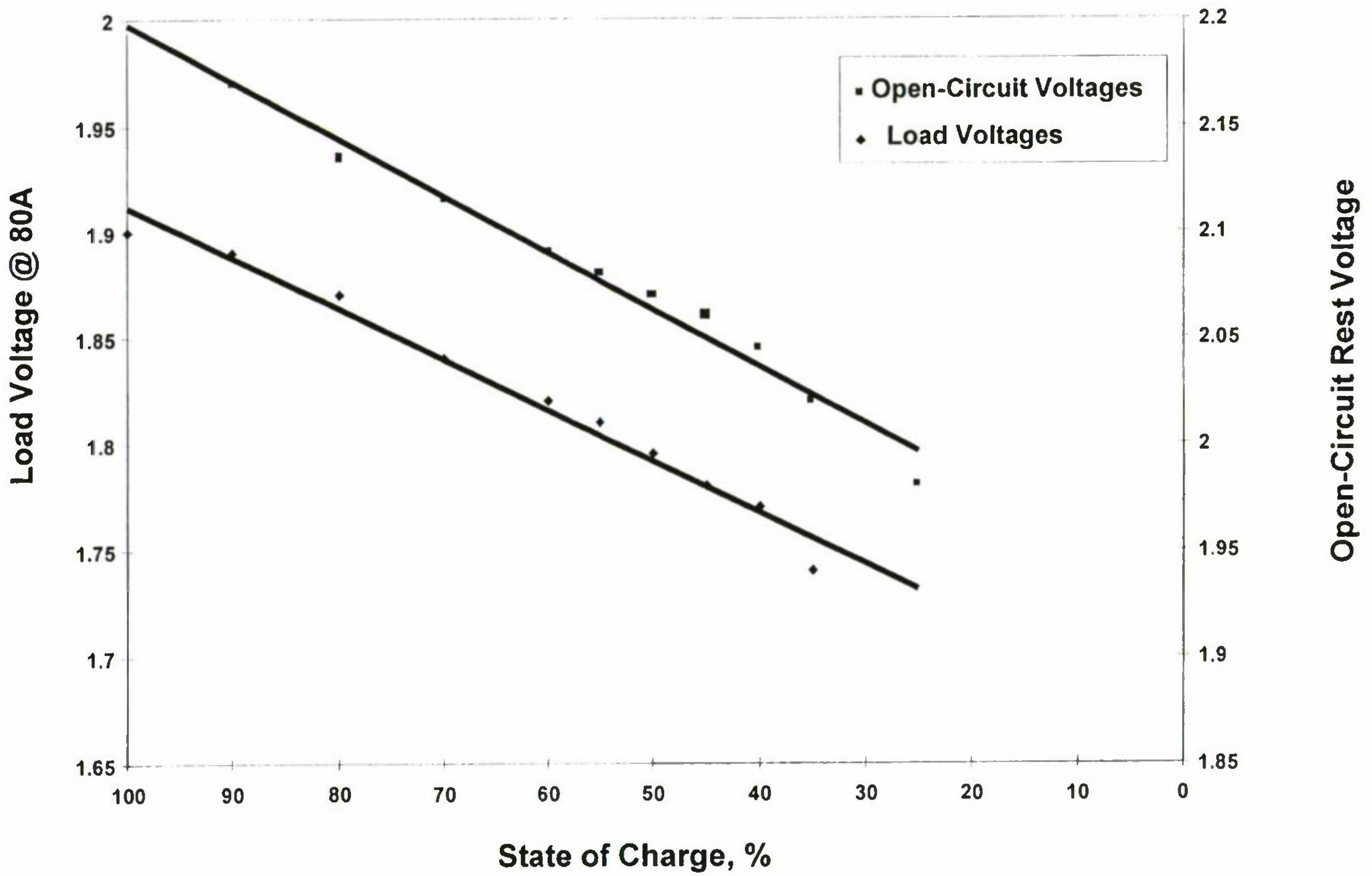
Peak Power (20 Second) Discharge

TMF 12 Volt, 2.4 Ah Battery



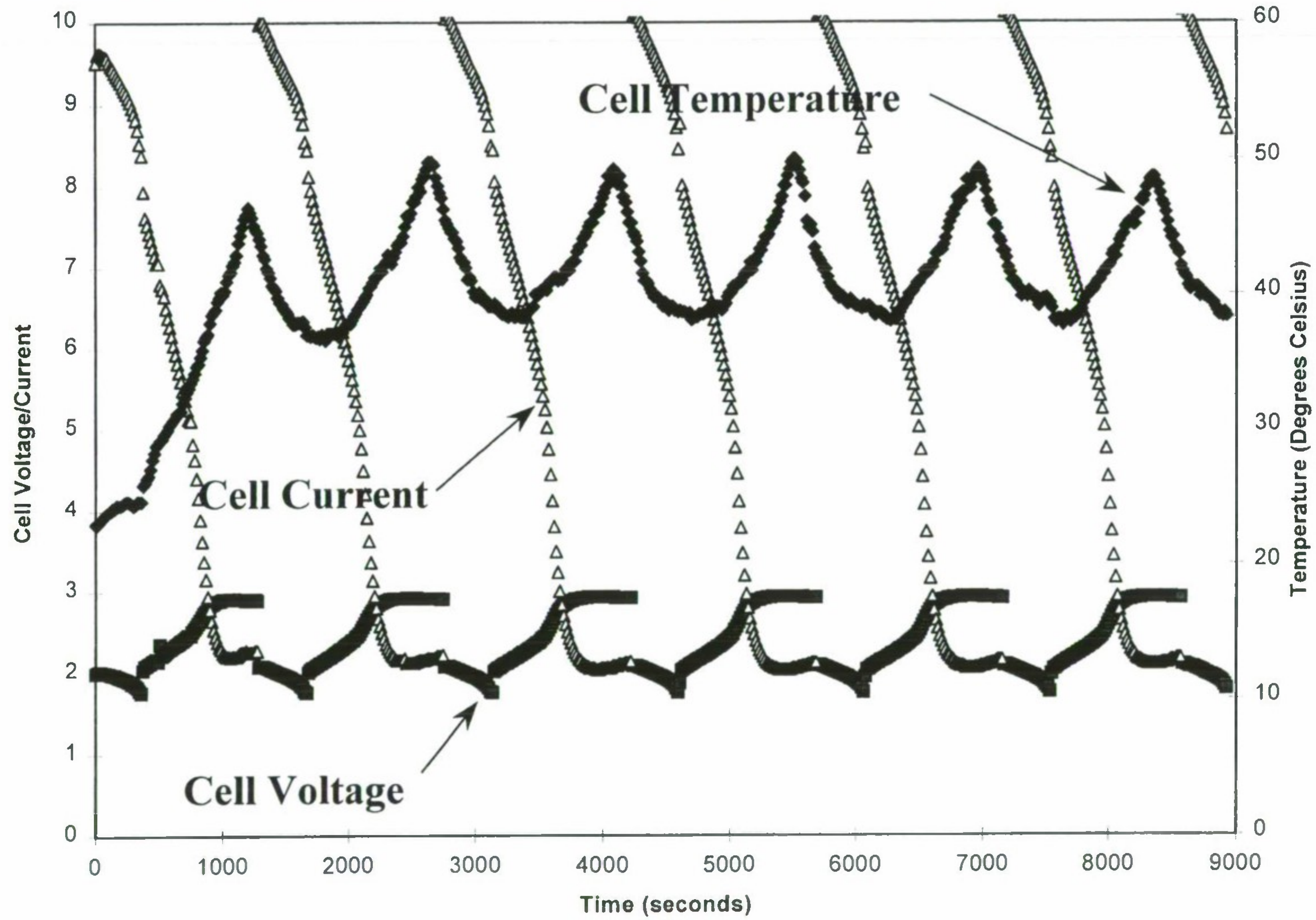
BOLDER TECHNOLOGIES CORPORATION

Voltages on Load and Open Circuit As a Function of State of Charge



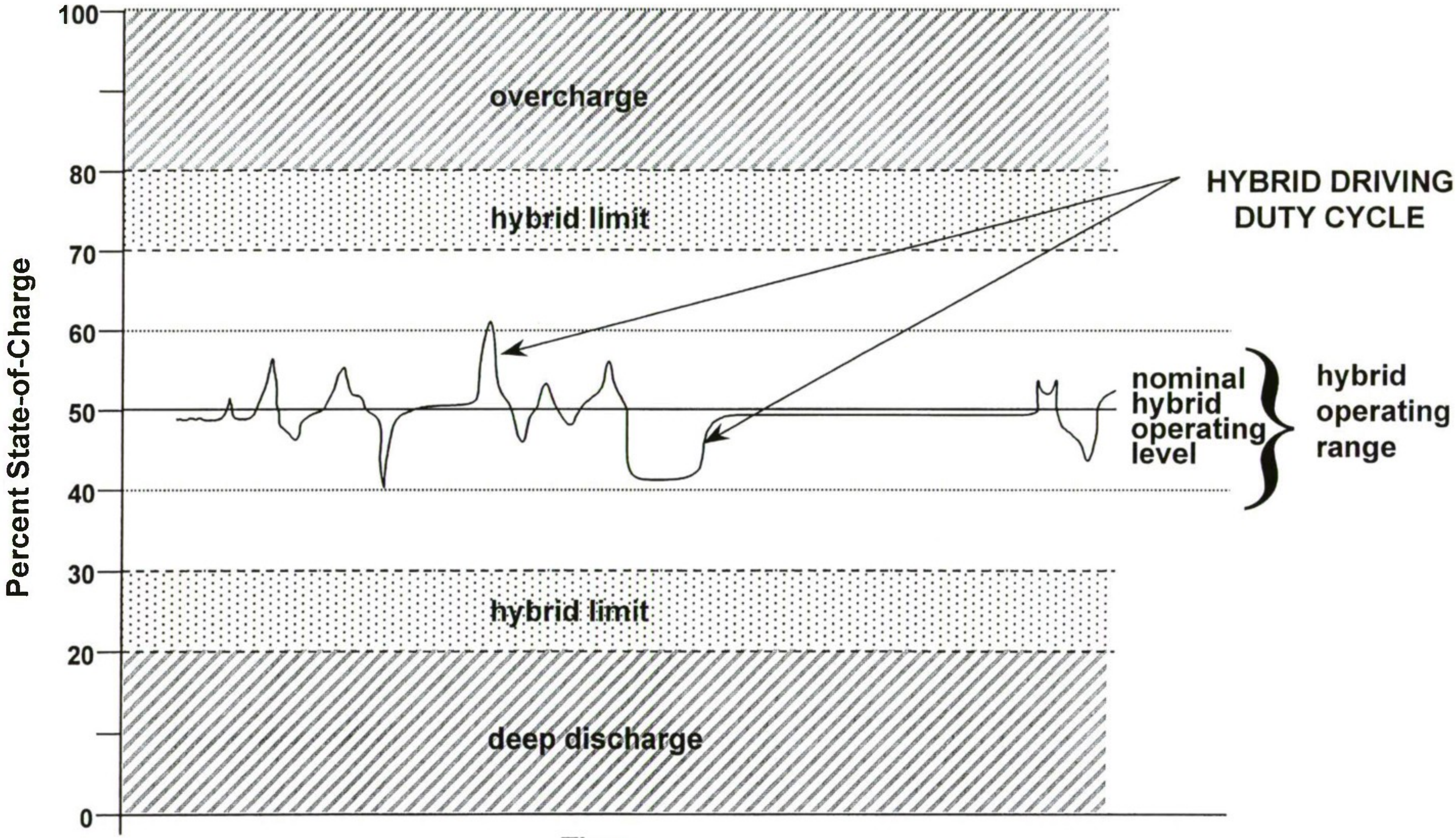
BOLDER TECHNOLOGIES CORPORATION

Discharge Across 0.20 Ohm Resistor (~10A) With 15-17 Minutes Recharge Continuous Cycle



BOLDER TECHNOLOGIES CORPORATION

State-of-Charge Considerations for Battery Hybrid Operation



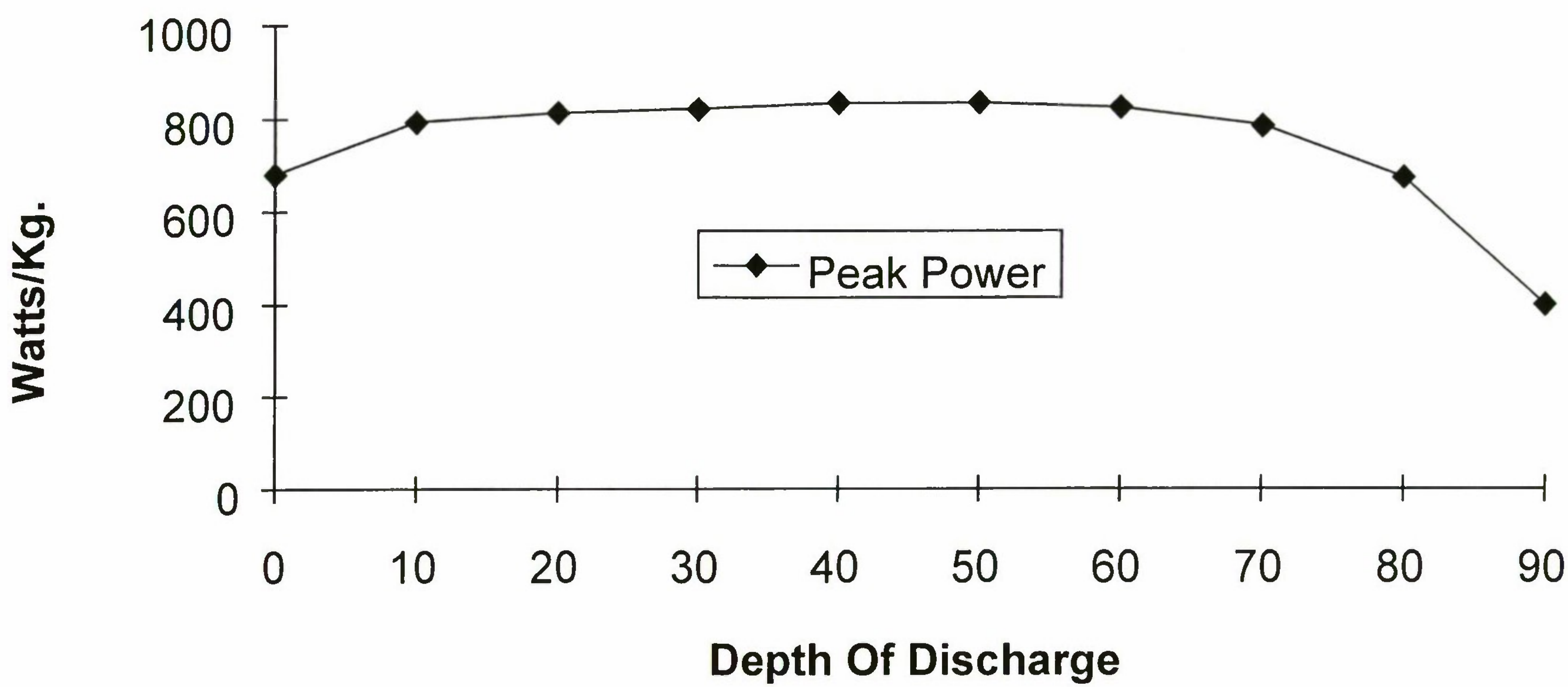
BOLDER TECHNOLOGIES CORPORATION

Requirements for Power-Assist HEV

- High Voltage System 300-360 V
- High Specific Power Levels, typically ~1kW/kg
- Reasonable Specific Energy at High Power Draw
- Minimal Battery Impedance, No Need for Thermal Management Hardware
- Peak Power Capability of ~ 100kW for 10 SECONDS
- Voltage Regulation Between ~1.70 to 2.5V Under Above Charge Discharge Conditions
- Accurate State of Charge Indicator
- Fast Response for Charge Delivery & Acceptance
- Easy to Service and/or Replace Modules

BOLDER TECHNOLOGIES CORPORATION

USABC Peak Power Test
BOLDER TMF Cells



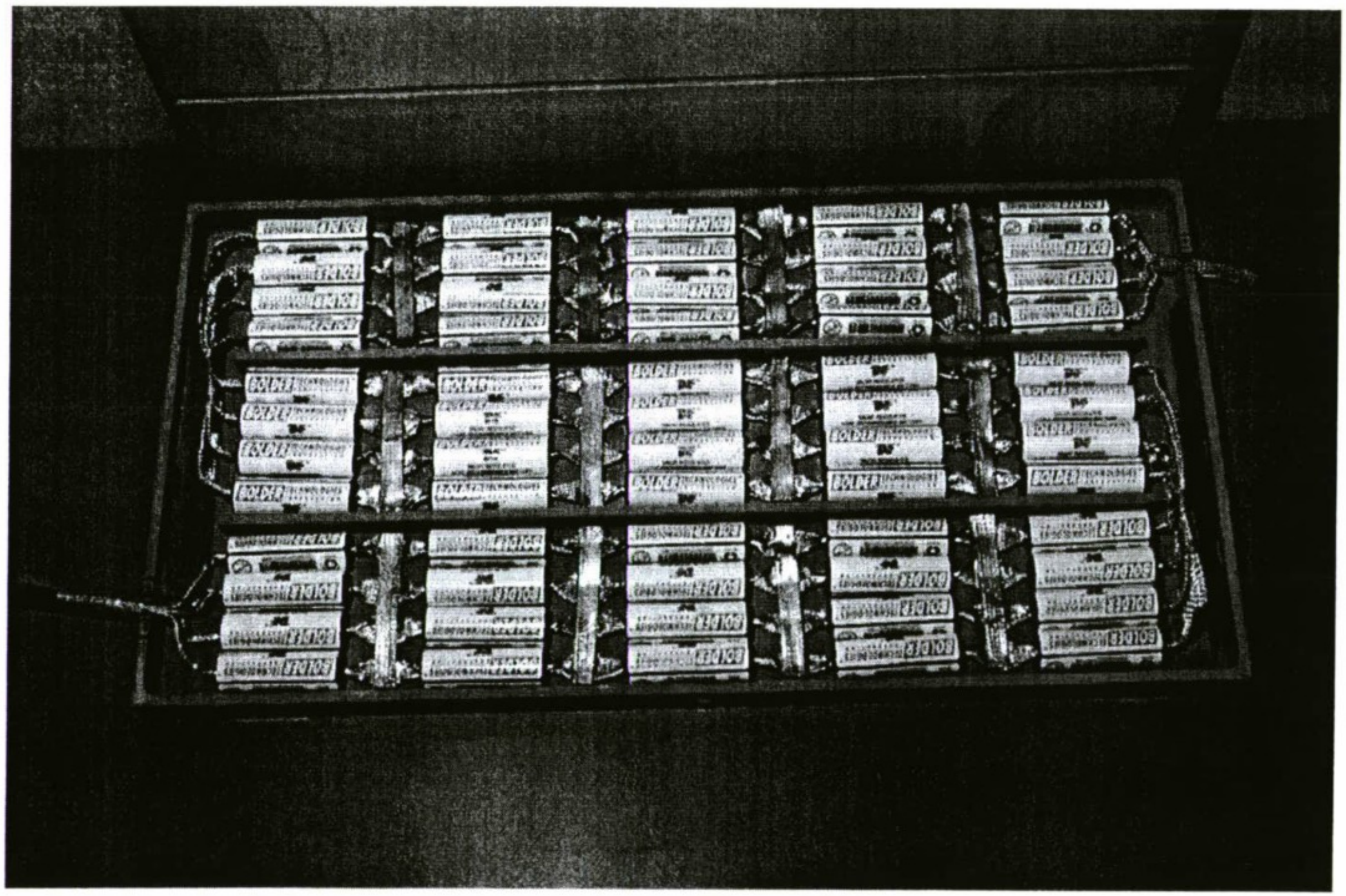
BOLDER TECHNOLOGIES CORPORATION

300 V/4.8 Ah Prototype Battery in Dodge Intrepid ESX

- Battery 4x150 Parallel-Series String (Cells were in 10 separate trays)
- Total Battery Size: 63”x33”x35”
- Battery Pack Mass: 91kg
- Cell Wt: 49kg
- Battery Impedance 61 Milli-Ohms

BOLDER TECHNOLOGIES CORPORATION

300 Volt Prototype Hybrid Vehicle Battery



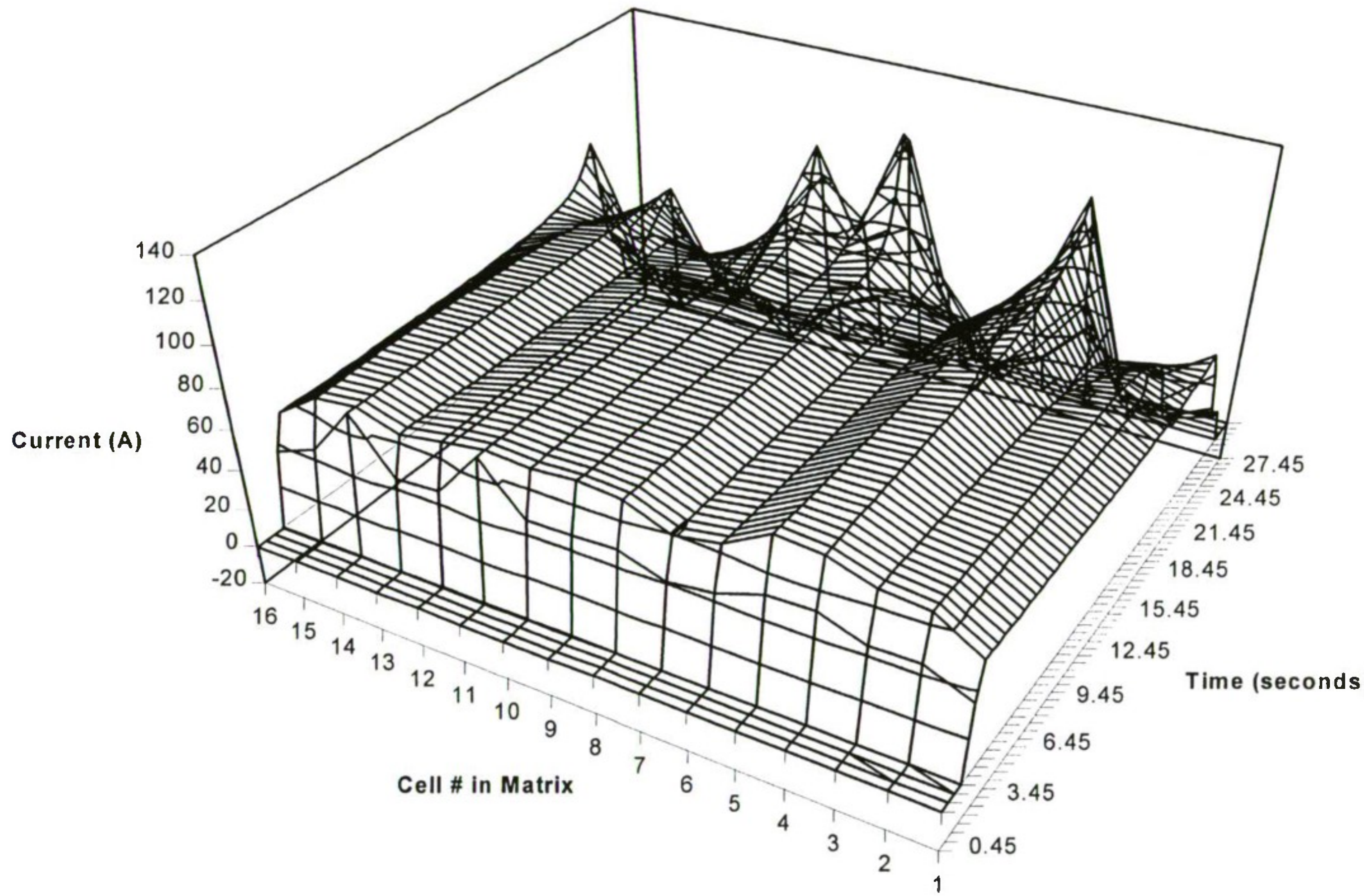
BOLDER TECHNOLOGIES CORPORATION

Load Leveling Test
4x4 Series-Parallel Matrix

- 16 Cells (4x4 Matrix) were subjected to 300A discharge from 100% SOC
- Discharge time and current of battery was recorded
- Battery sustained 300A for 27 seconds up to 90% DOD with uniform current distribution
- After 90% DOD the stronger cells prevailed

BOLDER TECHNOLOGIES CORPORATION

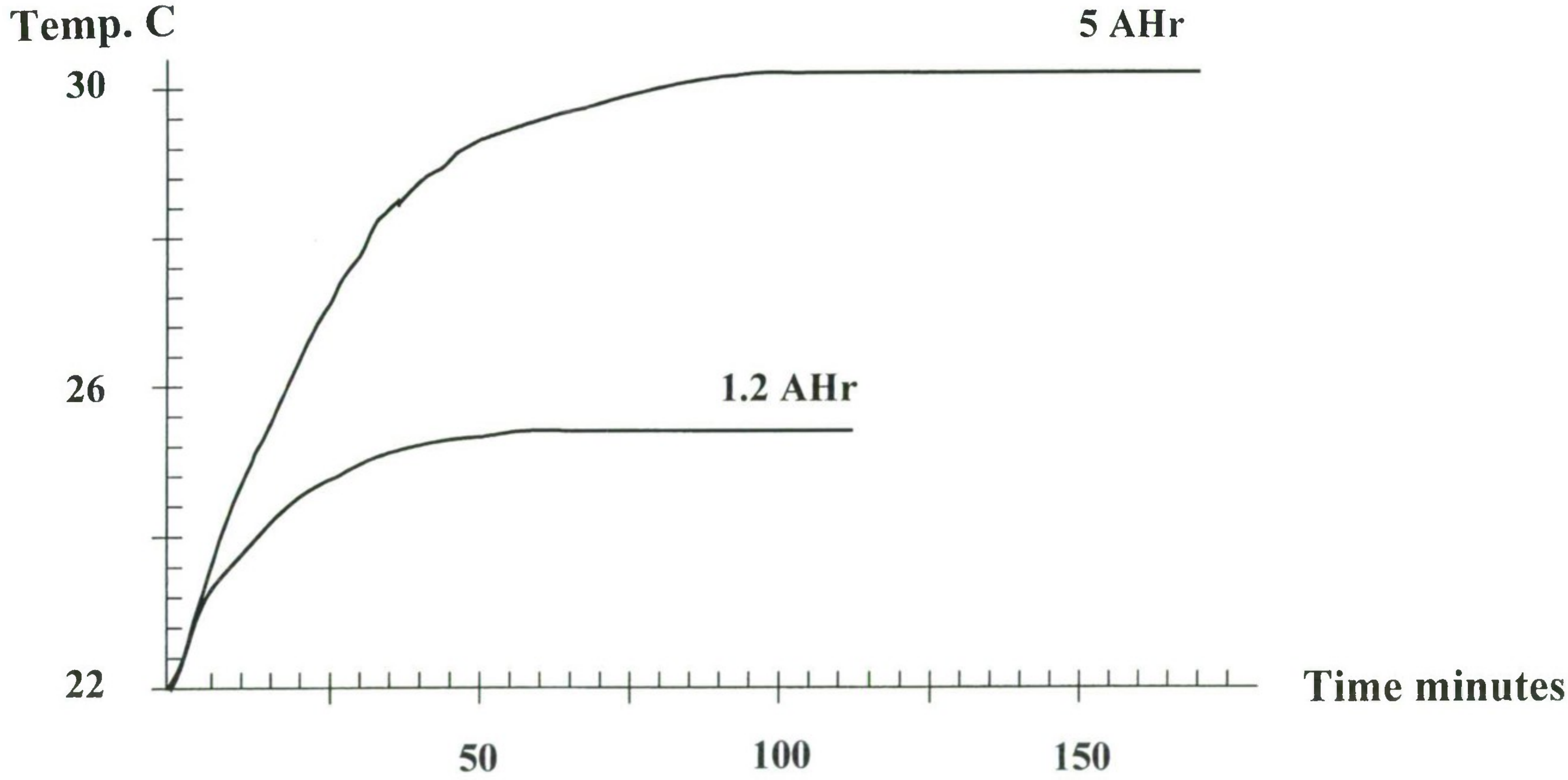
Simulated Hybrid Electric Vehicle Battery Testing 8V/4.8Ah Matrix of *Bolder* 1.0Ah Cells - 300 Amps Discharge



BOLDER TECHNOLOGIES CORPORATION

Thermal Management of *TMF*® Cell for HEV Application

Temperature profiles for 1.2 AHr & 5 AHr *TMF*® cells (Input: Avg. heat produced in HEV-GSFUDS test)



BOLDER TECHNOLOGIES

Conclusions

- High voltage battery system up to 360 V can be constructed
- *BOLDER TMF*® battery can provide stable power up to 70% DOD
- Peak power of ~1 kW can be provided
- No need for thermal management
- Fast response to current delivery and charge acceptance of regenerative breaking
- Voltage monitoring can provide accurate SOC
- Modules can be easily replaced
- *TMF* Technology is suitable for HEV

BOLDER TECHNOLOGIES CORPORATION

TMF® CELL SPECIFICATIONS

	1 AH CELL SPECS	5 AH PROTOTYPE CELLS SPECS	12 AH PROTOTYPE CELLS SPECS
Voltage:	2.15 V	2.15V	2.15V
Capacity:	1Ah@ 1C rate 50 A for 43 Seconds (.60 Ah)	5Ah @ 1C rate	12Ah @ 1C rate
Weight (lbs/gms):	.202/92	.9982/460	1.62-1.73/750-800
Dimensions:			
diameter (in/mm)	.90/22.9	1.929/49	2.8/71
length (in/mm)	2.76/70	3.200/82	2.75/70
Specific Energy (Wh/kg):	28	22	30
Energy Density (Wh/l):	78	67	86.9
Cell Impedance (mΩ):	1.4	0.3	0.3
Specific Power (W/kg):	4,439(5)	796(2a) 5329(2b)	800
Instantaneous Peak Power (W/kg):	4,400(4)	5,600(3)	TBD
Instantaneous Peak Power Density (W/l):	12,100(4)	16,500(3)	TBD

Notes:

(1) Conducted at 5 Ah.
(2) a. 200 amp discharge
b. Empirically derived for 1350 amps
(3) Short Circuit Test across 2K Amp Shunt (50 Micro-Ohm Resistance)
(4) At 1,000 Amps – actual short circuit current > 1200 amps
(5) At 270 Amps

1999 VEHICLES TECHNOLOGIES ALTERNATIVE PROPULSION SYMPOSIUM

Fuel Cell Powered Transit Bus Program

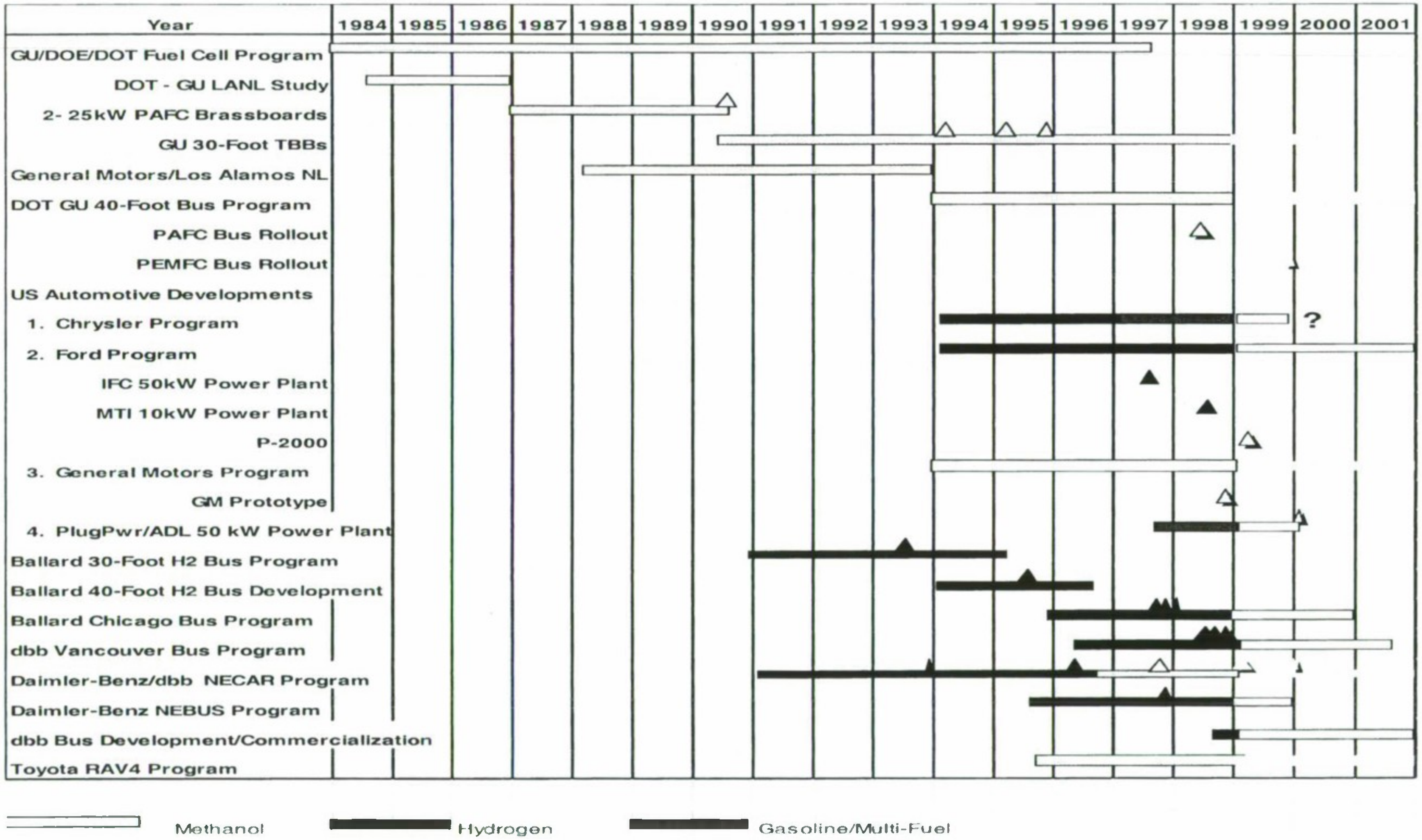
May 3-5, 1999

James T. Larkins
Georgetown University
(202) 687-7361
larkinsj@gunet.georgetown.edu

OVERVIEW

- Transportation Fuel Cell development activities
- GU Program Overview
  - 1st generation buses (30-foot)
  - 2nd generation bus (40-foot PAFC)
  - 2nd generation bus (40-foot PEMFC)
- Future Plans
  - FTA Memorandum of Agreement
  - Hybrid Vs. Non-hybrid Operation

Worldwide Trends In Transportation Fuel Cell



WHAT IS A FUEL CELL

- The Fuel Cell (FC) is an Electro-chemical power source
  - Utility power
  - Special Residential power
  - Emergency no-break power
  - Transportation power
    - » Automobiles, buses, trucks & trains

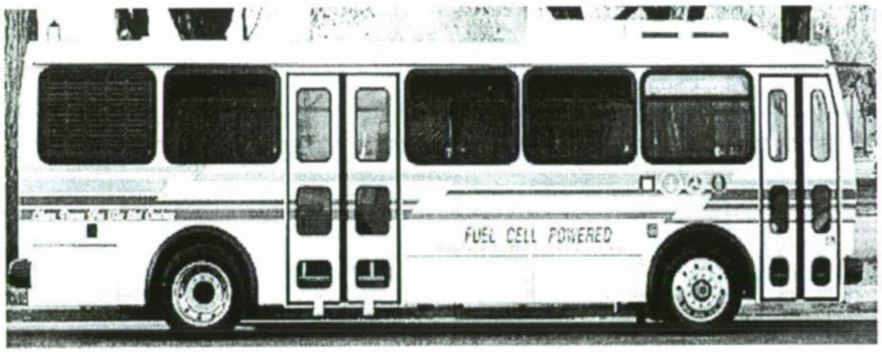
AUTOMOBILE VERSUS BUS CHARACTERISTICS

Parameter	Automobile	Bus
Power (kW)	50-100	200
Start-up	>10 sec.	~15 min.
ICE efficiency	15-25%	25-32%
Allowable weight (lbs.)	~ 1000	~ 3500
Allowable volume (ft^3.)	~10-12	~250
Operating Life (hrs.)	3000-5000	>25,000

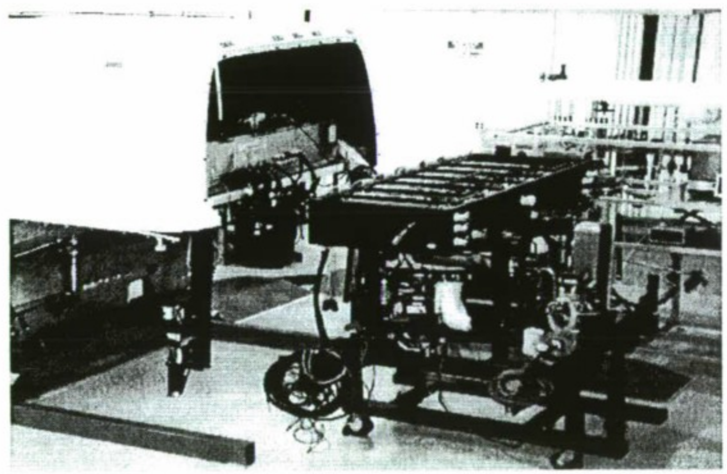
GU's 15 YEAR HISTORY with LIQUID FUELED FUEL CELL VEHICLES

- First vehicle-type liquid-fueled 25 kW Fuel Cells - 1989
- World's first liquid-fueled Fuel Cell vehicle- 1994
- Operated and tested three 30-foot Test Bed Buses
- Demonstrated "commercially viable" full size (40-foot) bus in May, 1998 - 100 kW PAFC
- 100 kW PEMFC now being tested
  - Planned for bus rollout in fall 1999
- Will complete a stable of operating Fuel Cell vehicles

FUEL CELL POWERED BUS EVOLUTION



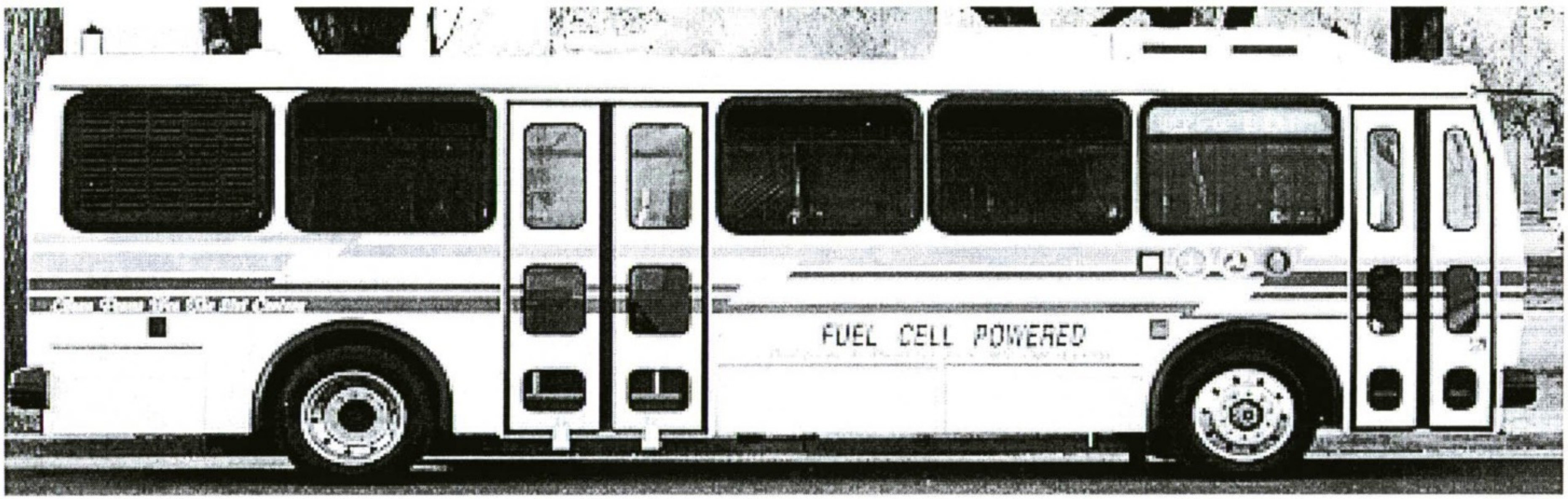
30-Foot Test Bed Buses (3)



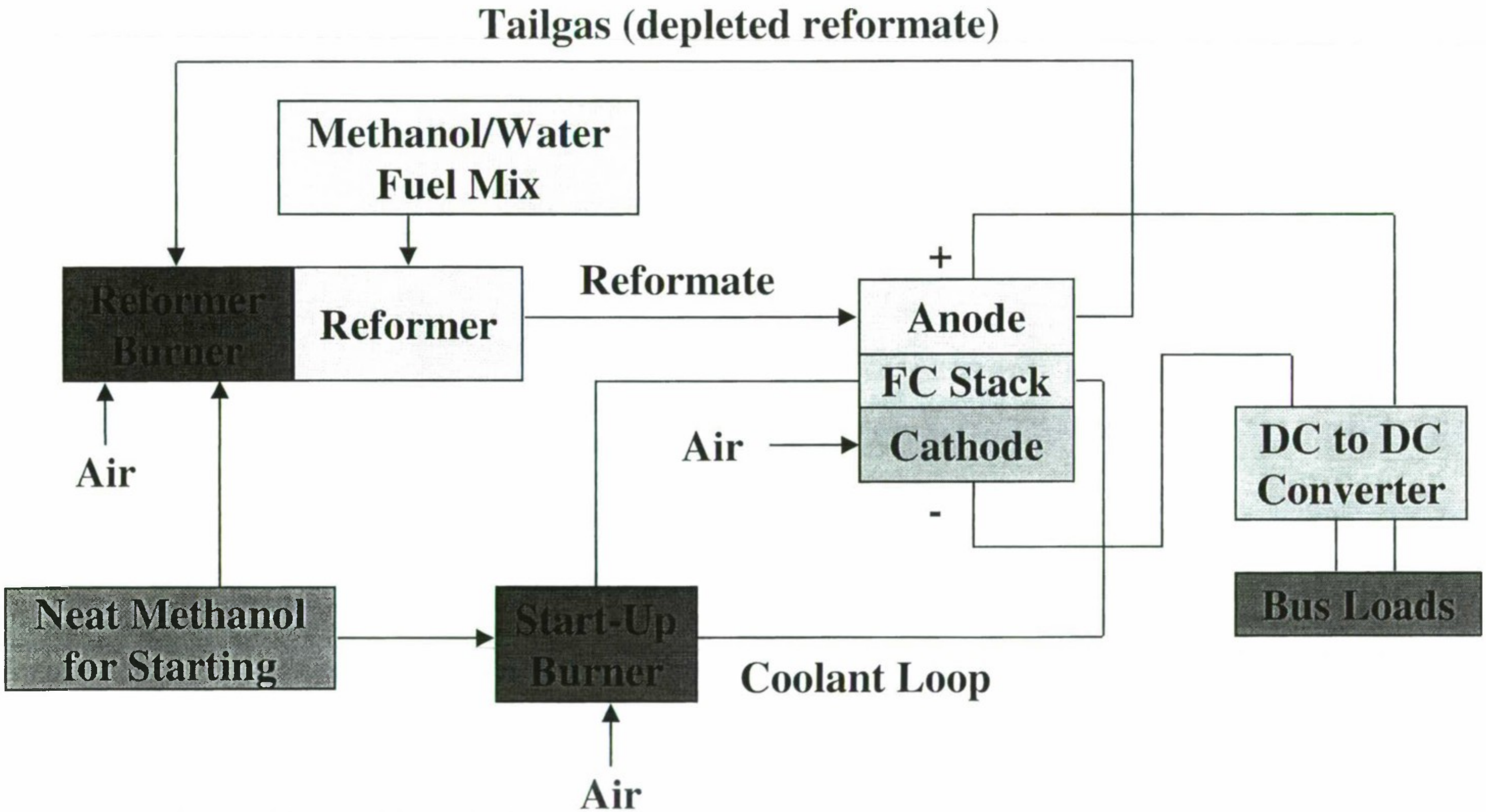
100 kW PEMFC Power Plant

40-Foot 100 kW PAFC Bus

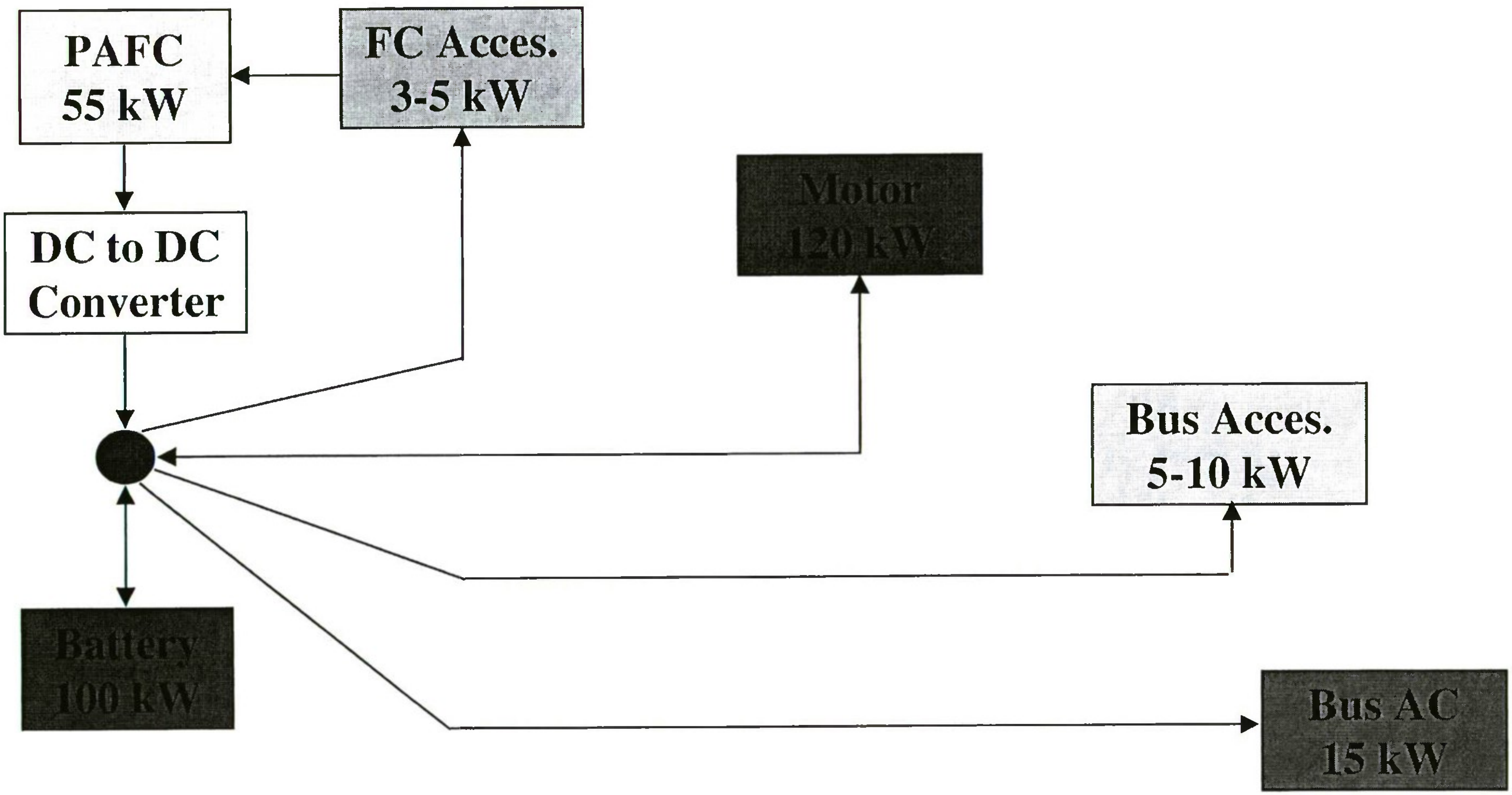
30-Foot FUEL CELL POWERED BUS



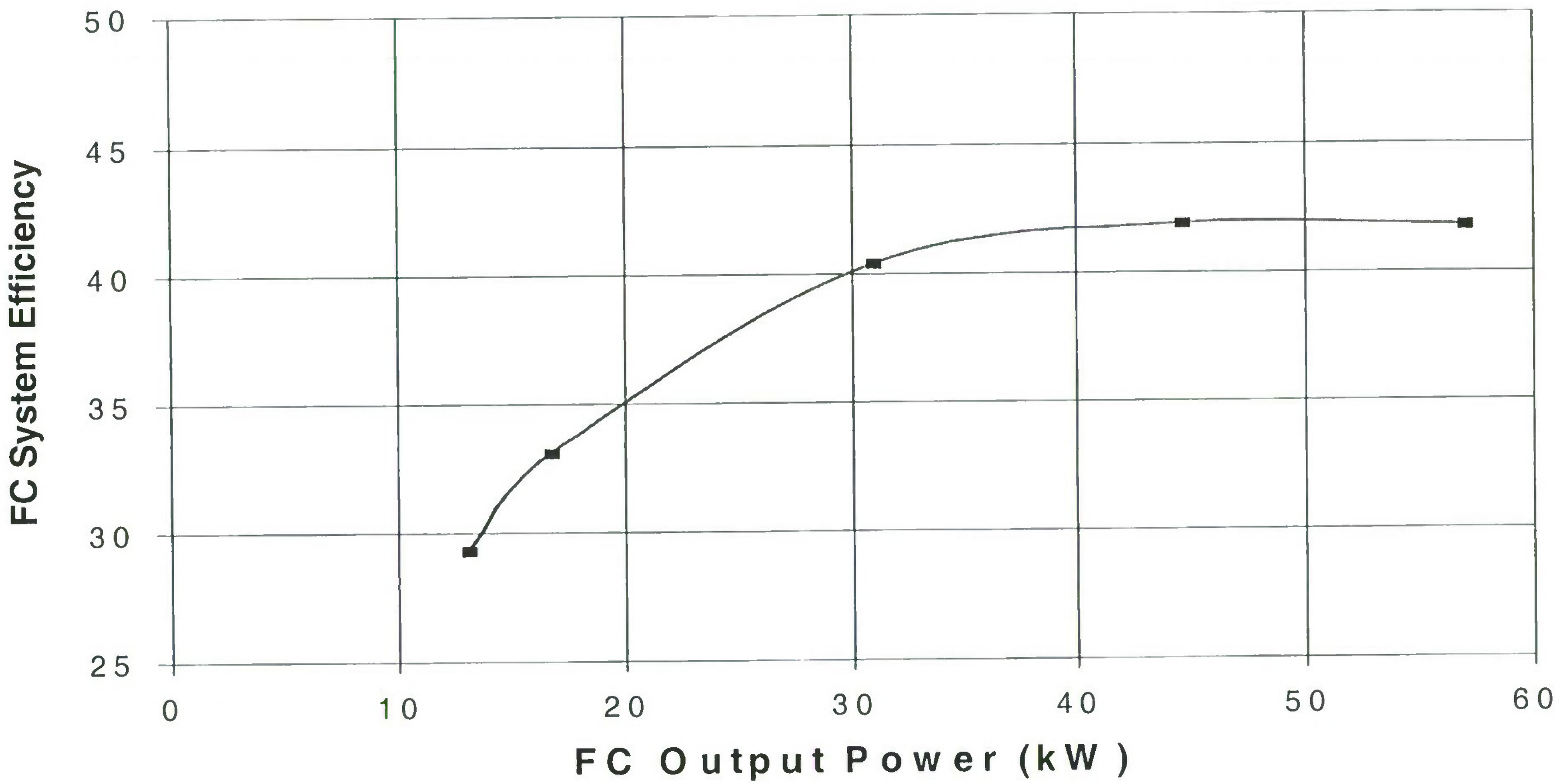
30-Foot FUEL CELL SYSTEM SCHEMATIC



30-Foot BUS HYBRID SYSTEM BLOCK DIAGRAM



FUJI FUEL CELL SYSTEM EFFICIENCY



Based on LHV of methanol and with FCS accessories included

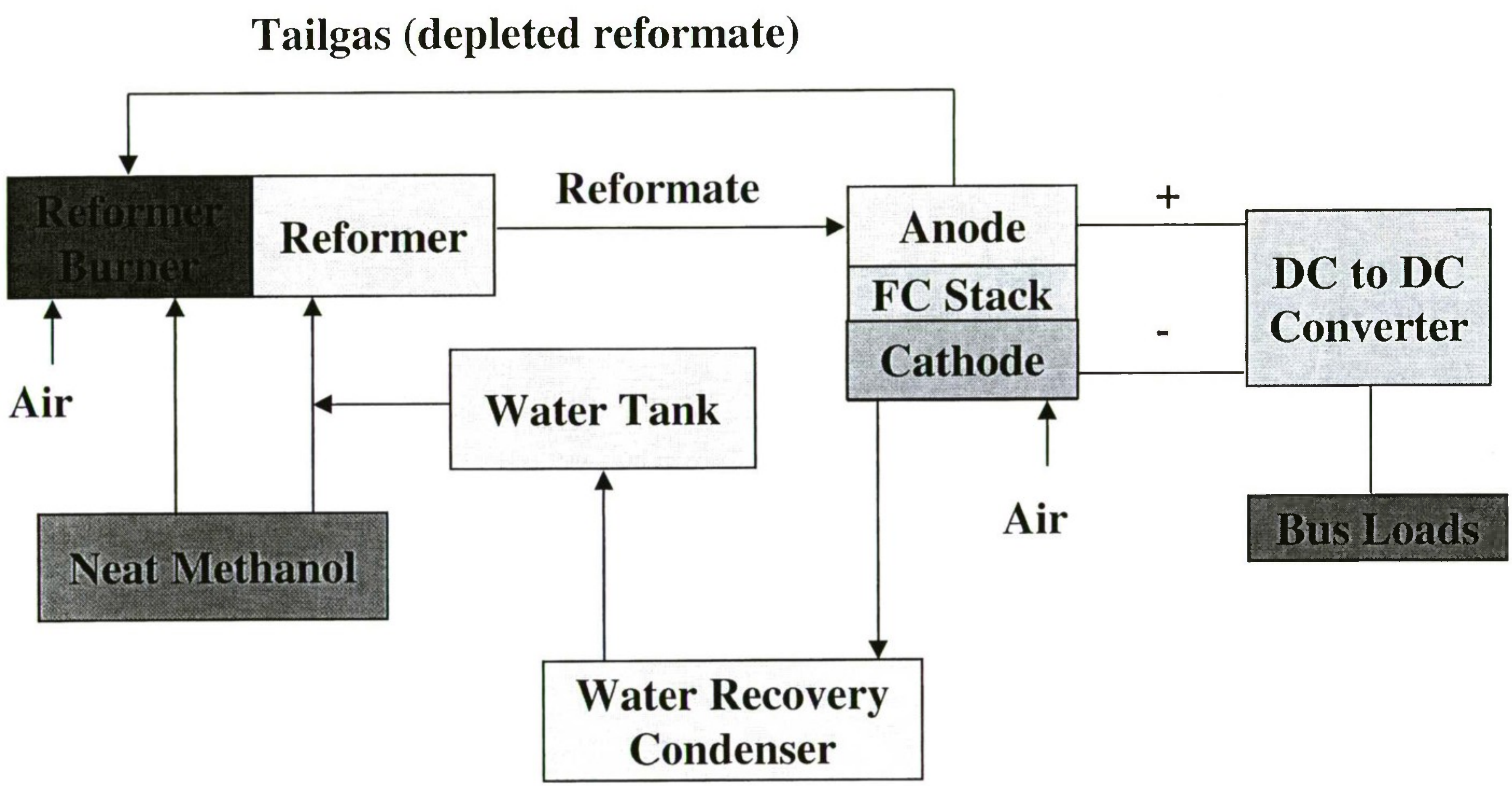
COMPARISON of STEADY-STATE FUEL CELL EMISSIONS

Line	Fuel	Power Plant	HC	CO	NOx	PM
1	98 Standards		1.30	15.50	4.00	0.05
2	Diesel	DD Series 50*	0.10	0.90	4.70	0.04
3	CNG	DD Series 50	0.80	2.60	1.90	0.03
4	Diesel	Cummins C8.3	0.20	0.50	4.90	0.06
5	CNG	Cummins C8.3	0.10	1.00	2.60	0.01
6	Methanol	94 Fuji Fuel Cell	0.09	2.87	0.03	0.01
7	Methanol	98 IFC Fuel Cell**	<0.01	<0.02	~0.0	~0.0
* With catalytic converter			** IFC test results			

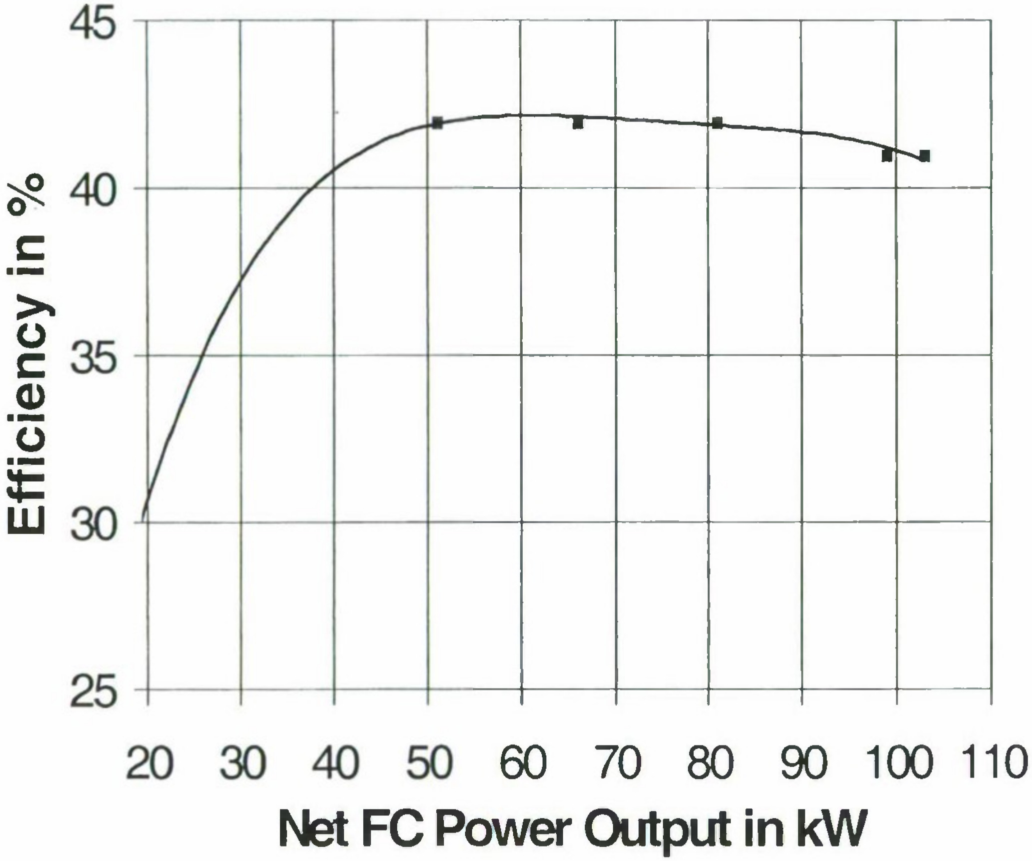
All emission values in g/bhp-hr

40-Foot FUEL CELL POWERED TRANSIT BUS

40-Foot BUS FUEL CELL SYSTEM SCHEMATIC



100 kW IFC PAFC FOR 40-Foot BUS



System Emissions

CO......0.02 g/kW-hr

HC......0.01 g/kW-hr

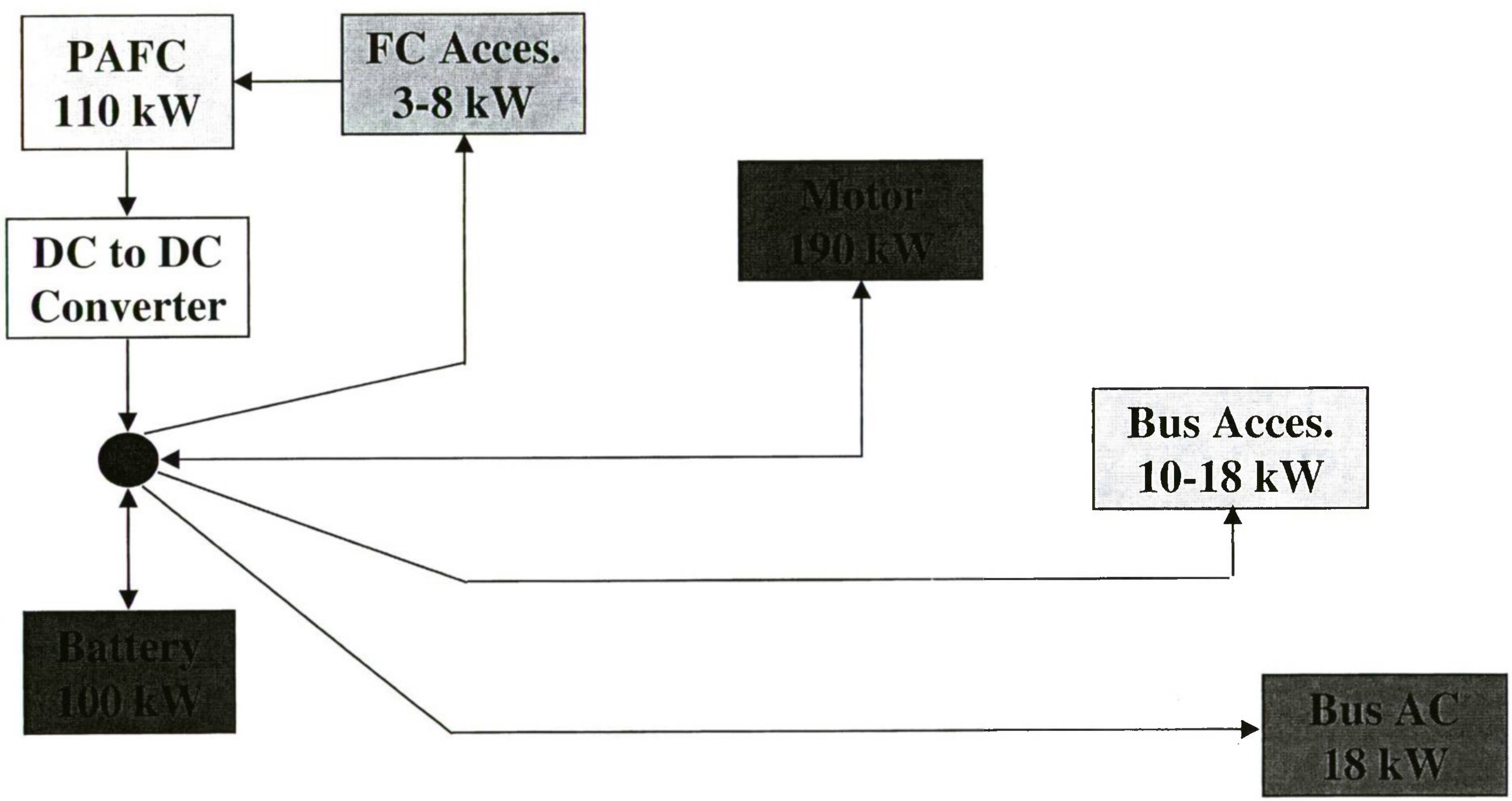
NO_X....Undetectable

PM......Undetectable

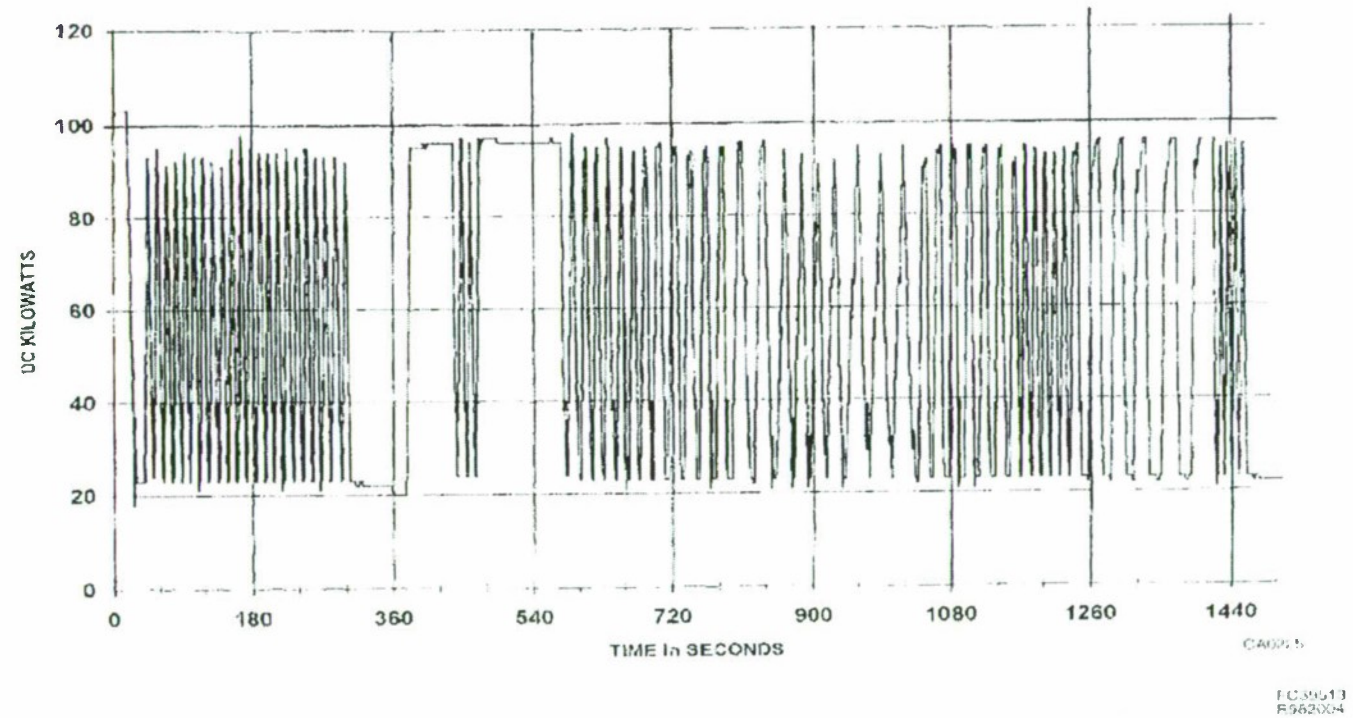
Efficiency based on:

* LHV of methanol
* 6.8 kW of FCS accessories

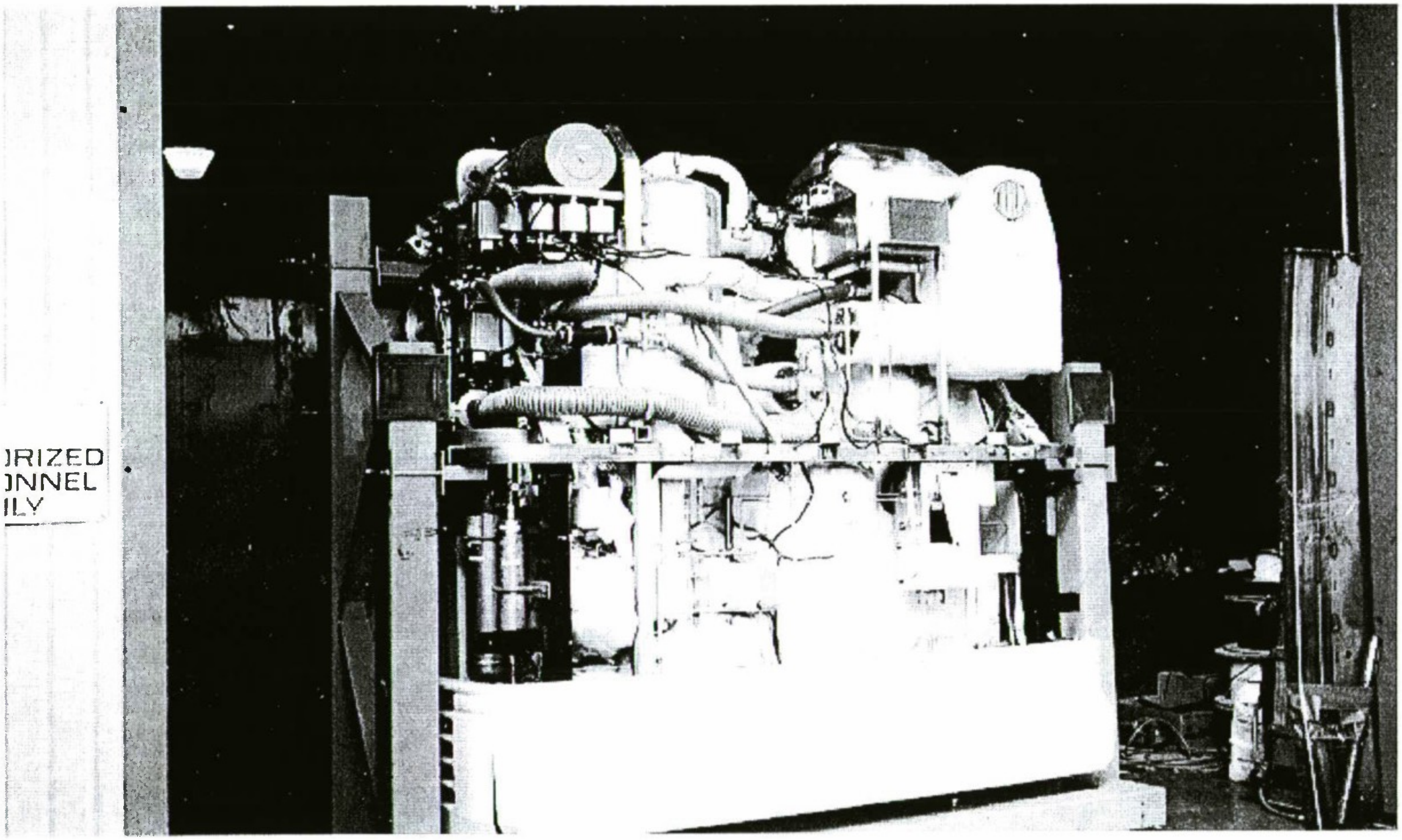
40-Foot BUS HYBRID SYSTEM BLOCK DIAGRAM



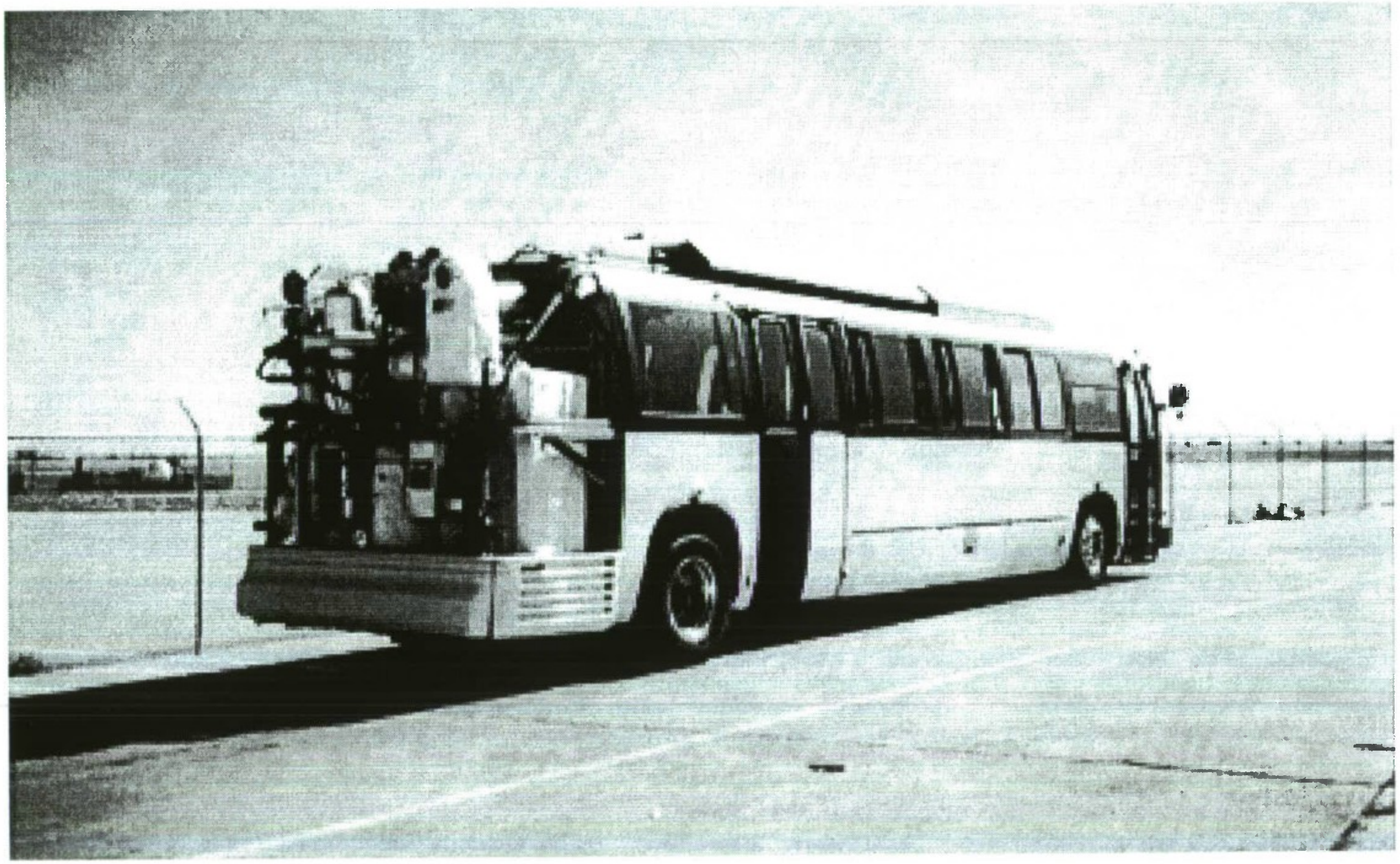
40-Foot BUS FUEL CELL POWER SYSTEM TRANSIENT CAPABILITY



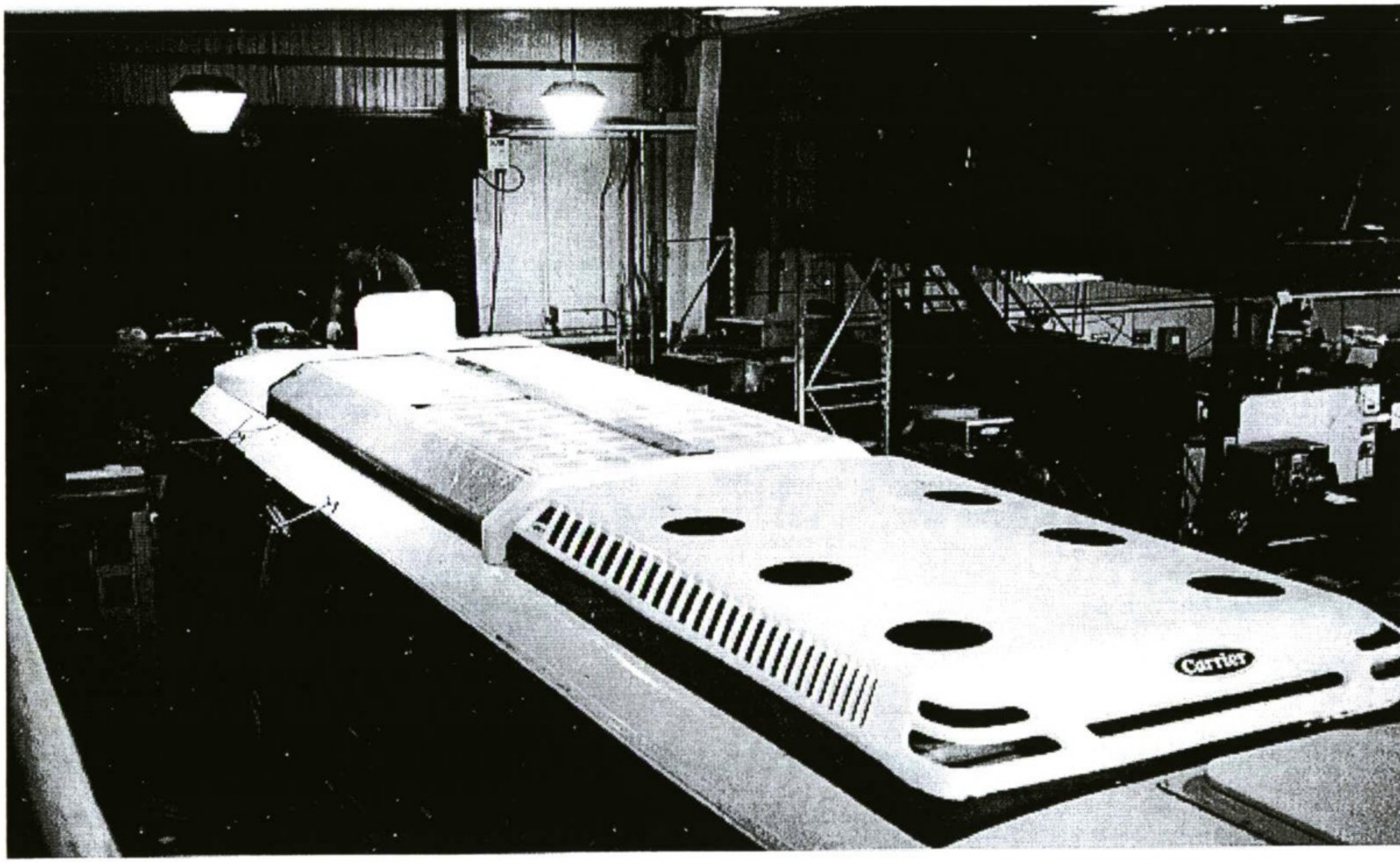
100 kW IFC PAFC in SHIPPING FIXTURE



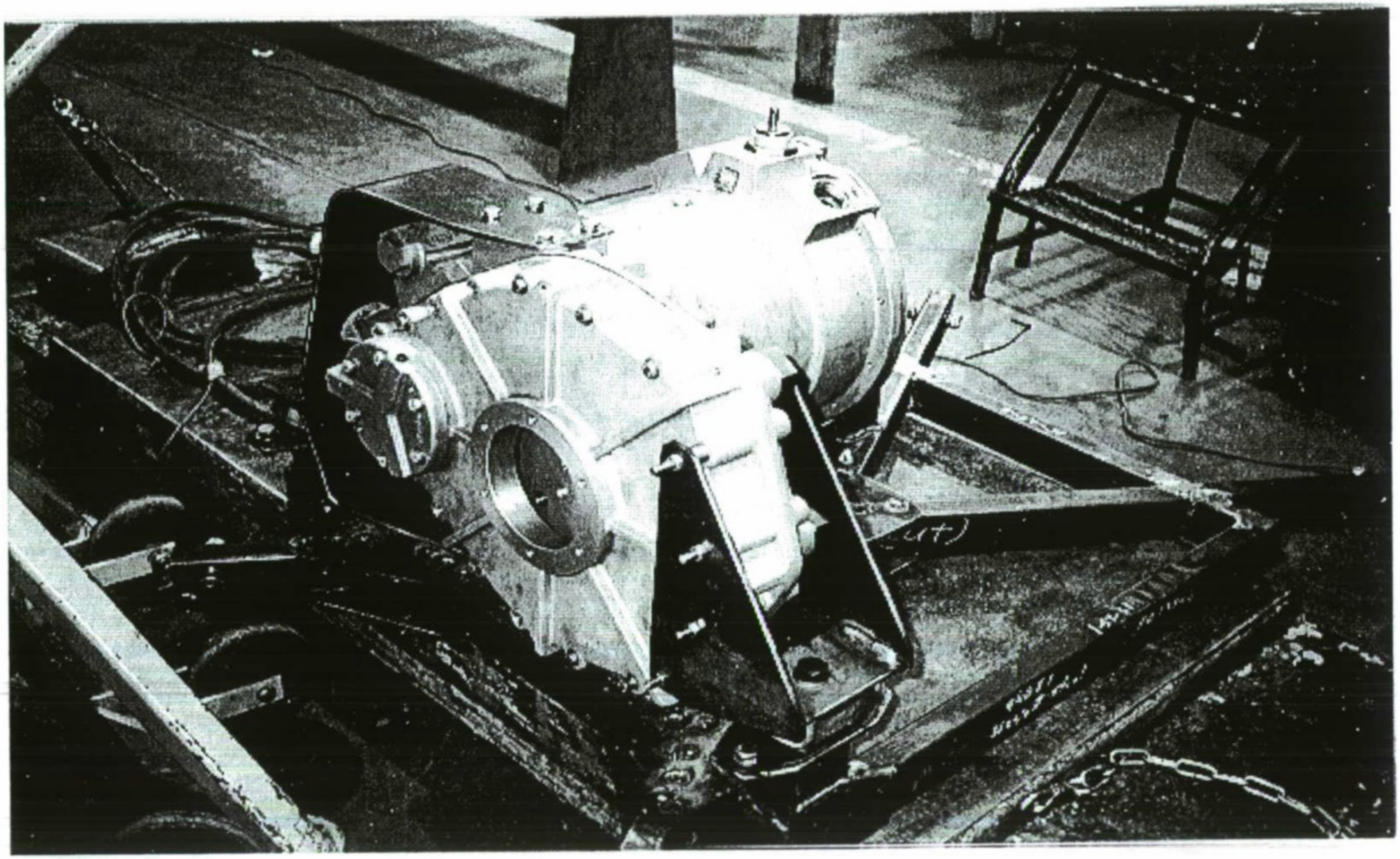
100 kW IFC PAFC POWER PLANT MOUNTED ON BUS



AIR CONDITIONING and COOLING RADIATOR



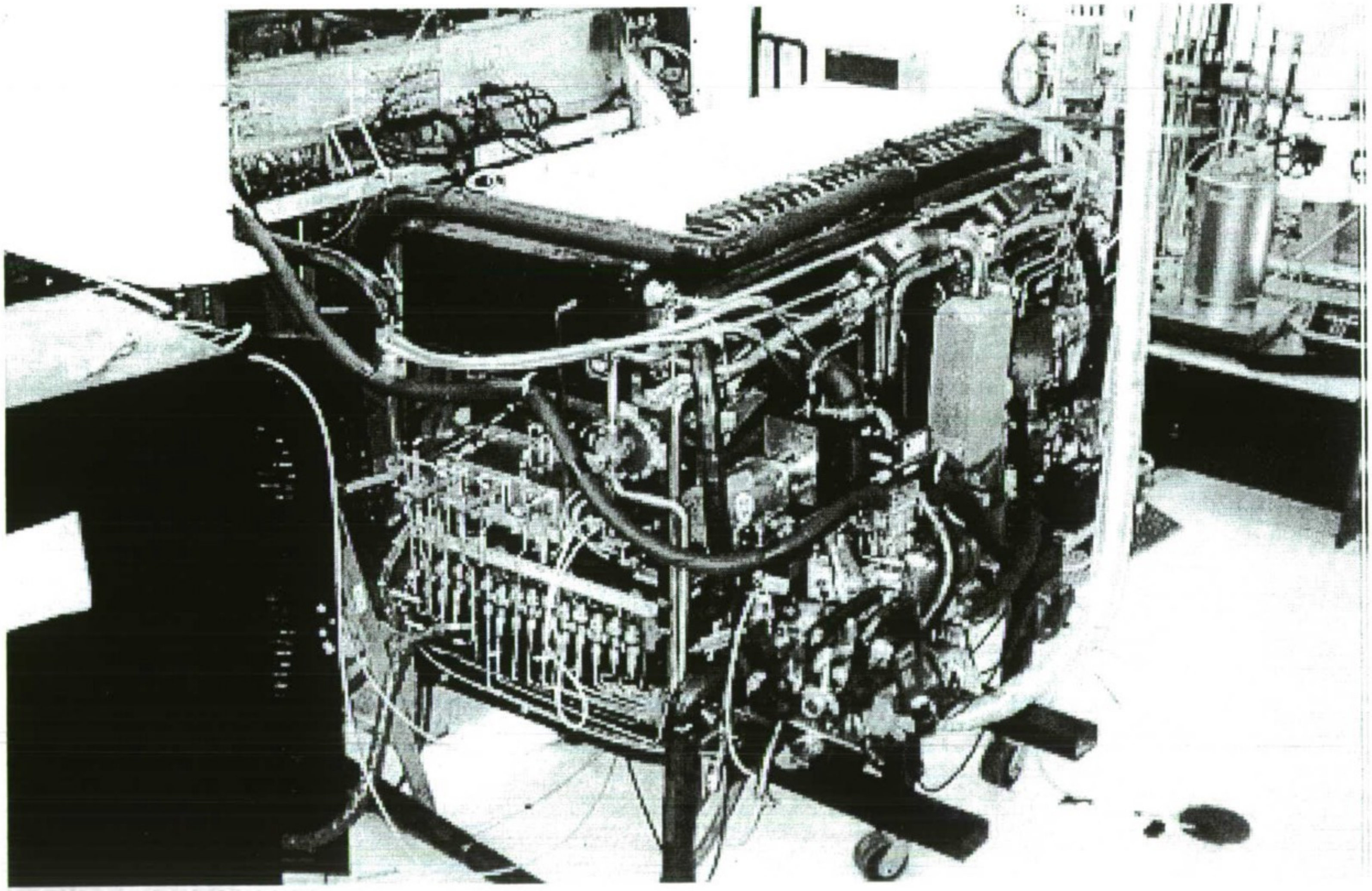
250 Hp AC INDUCTION MOTOR and GEARBOX



dbb 100 kW PEMFC DESIGN PHILOSOPHY

- Two 50 kW modules
- NeCar III technology
- 700 Series Ballard Stacks
- Increased capacity Fuel processors
- Parallel fuel streams - tied electrically

dbb 100 kW PEMFC BUS POWER PLANT



CONCLUSION

- Transportation Fuel Cells are here
- Demonstrations and testing have validated technology readiness for the transit bus application
- Test results confirm environmental and efficiency benefits
- Must develop and test full-up vehicles to optimize performance and address system issues
- Georgetown University will have a stable of Fuel Cell powered transit buses by end of 1999

TACOM

Mobility and Firepower
for America's Army

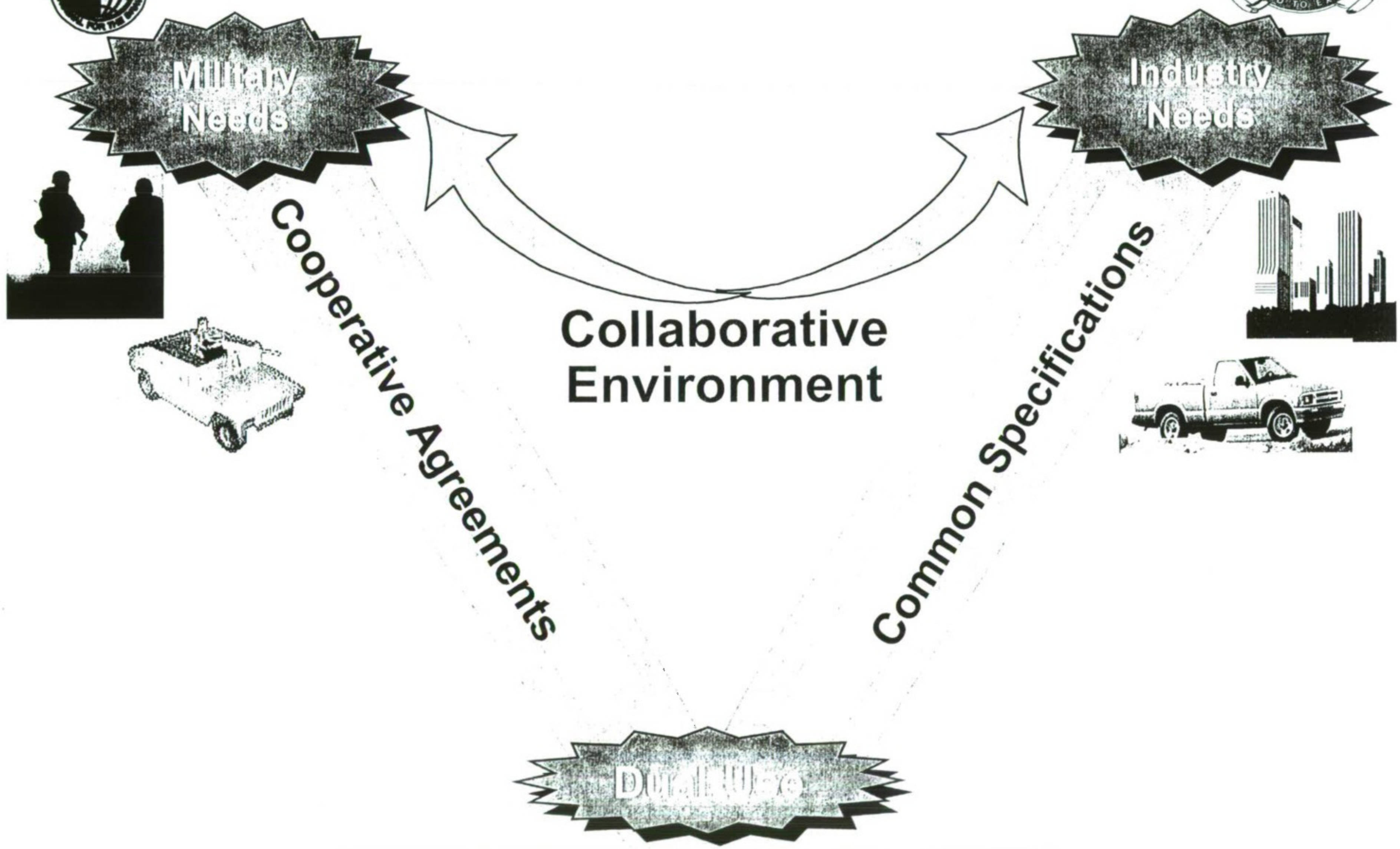
Military Goals in Diesel Reformer Development for Fuel Cell Applications

Herbert H. Dobbs, Jr.
U.S. Army TACOM
May 4, 1999

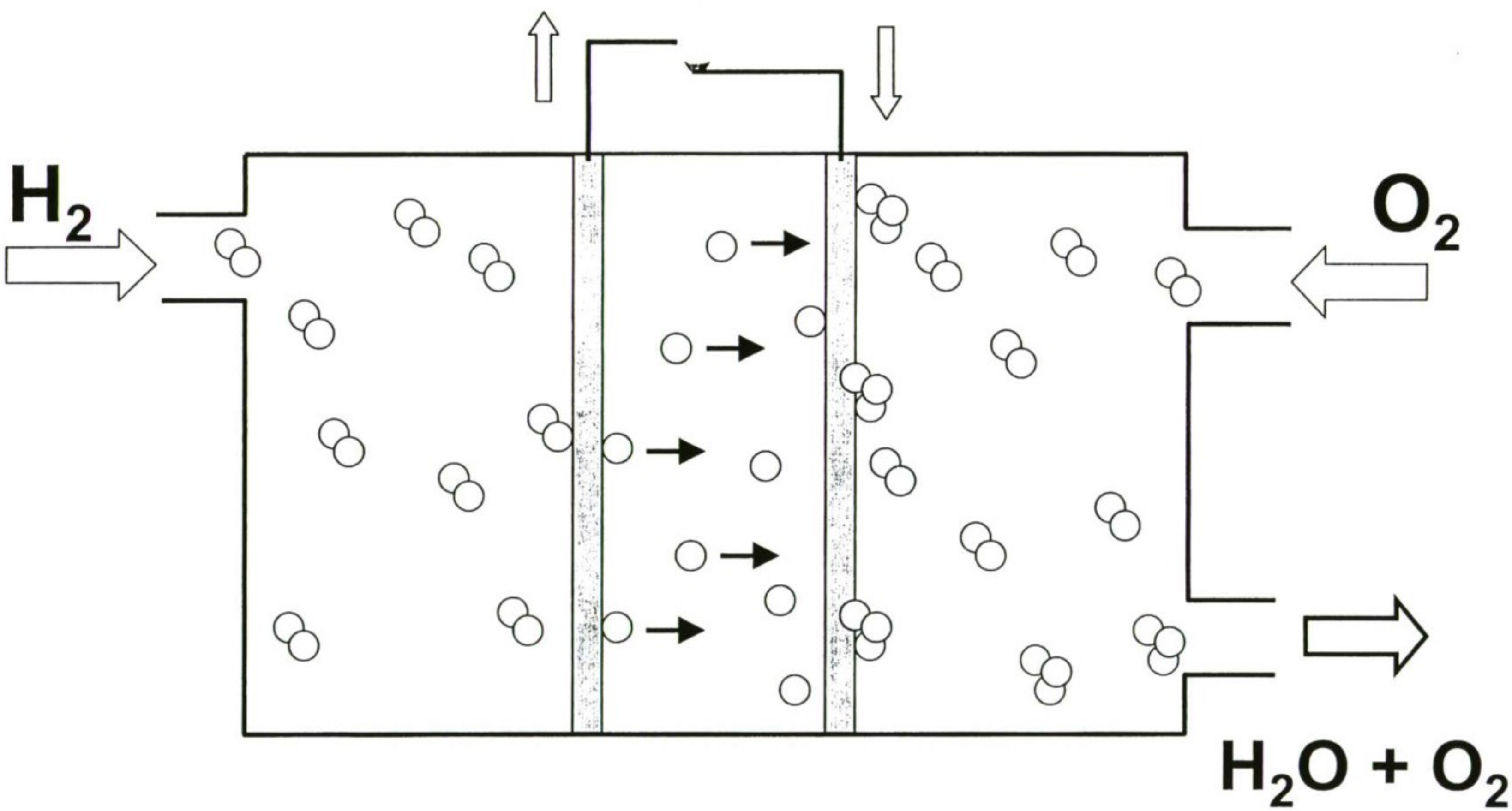
Outline

- ***NAC Overview***
- ***Technology Basics***
- ***Fuel Cell Engines and Military Trucks***
- ***Technology Issues and Challenges***
- ***NAC Initiative in Diesel Reforming***
- ***Emerging Technology***

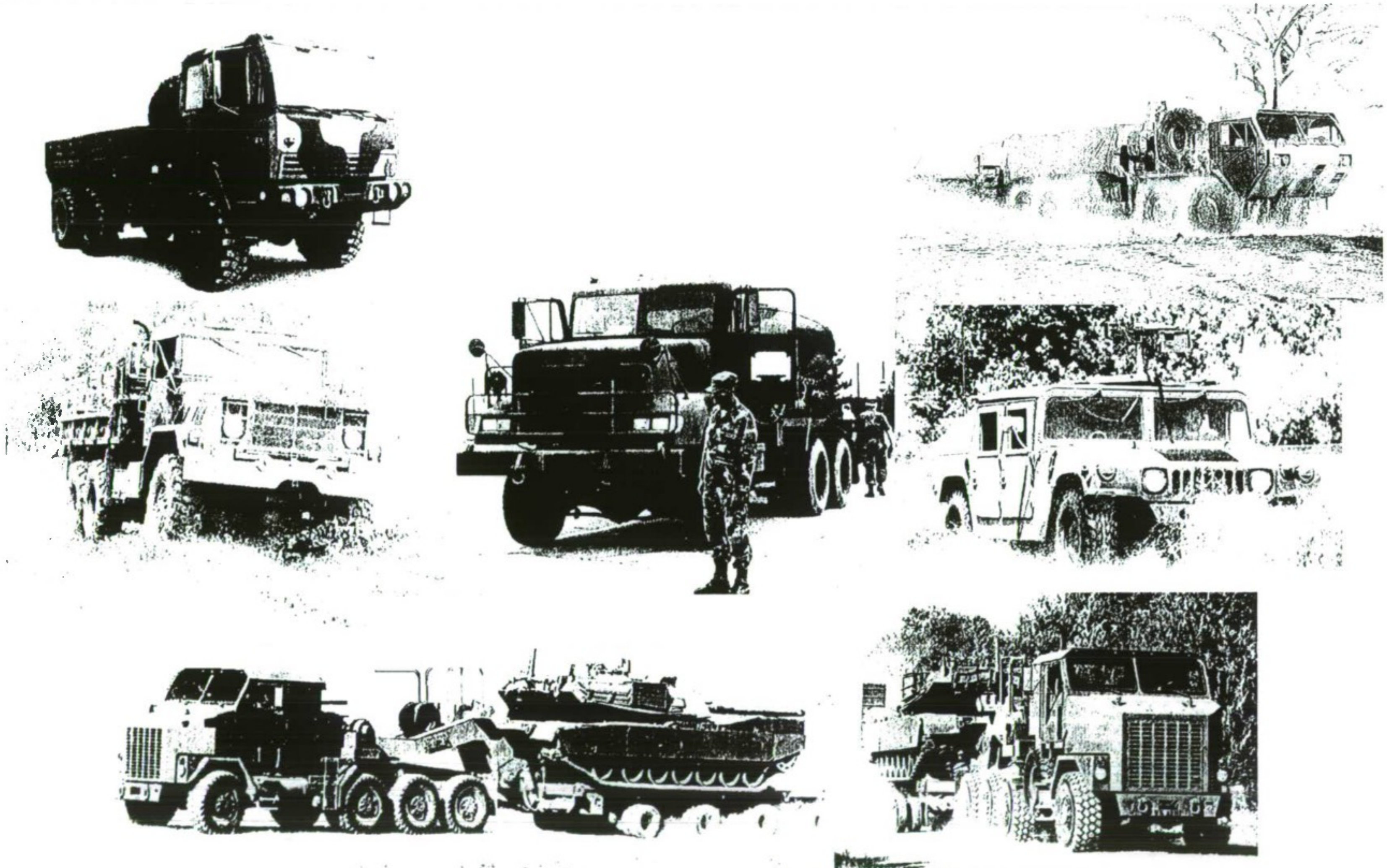
Dual-Needs Focus



Fuel Cell Basics



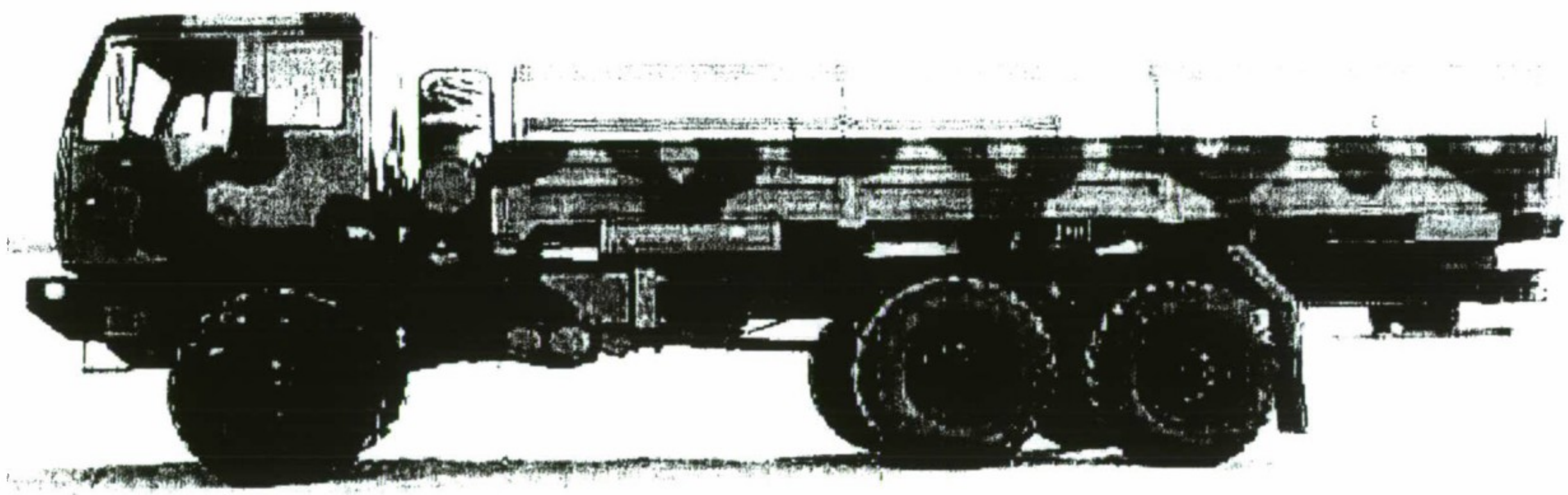
The Army Tactical Fleet



Commercial Directions in Fuel Cell Propulsion

- **Emissions Driven**
- **20-40,000 fuel cell cars by 2004-2005**
- **Methanol, Gasoline or hydrogen fuel**
- **Fuel cell-hybrid or straight fuel cell power**
- **Heavy electric and hybrid drives emerging**

M1085 5-Ton Truck



Unresolved Commercial Fuel Cell Propulsion Issues

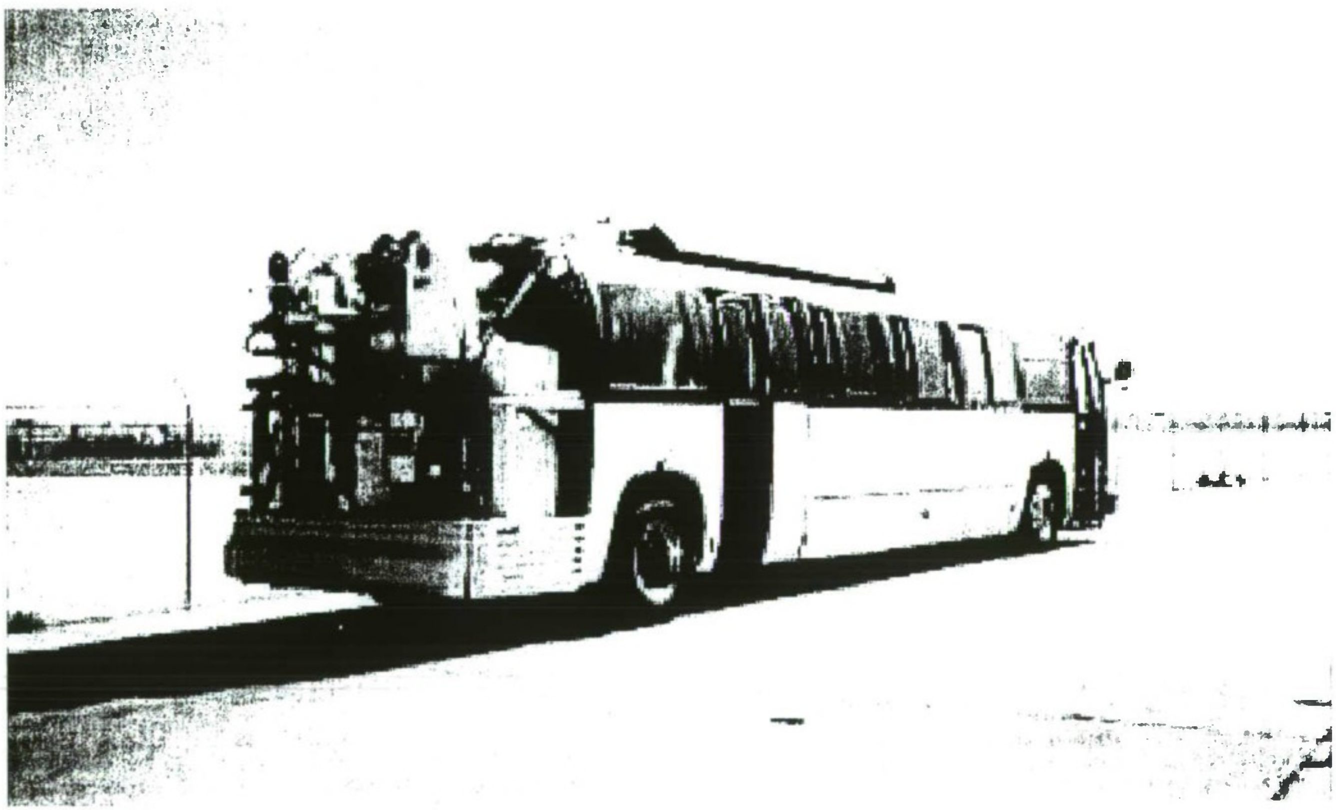
- Methanol vs. gasoline reformers
- Fuel cell hybrid vs. straight fuel cell
- Cold weather operation
- Heat rejection
- Transient response

Military Issues for Fuel Cell Propulsion

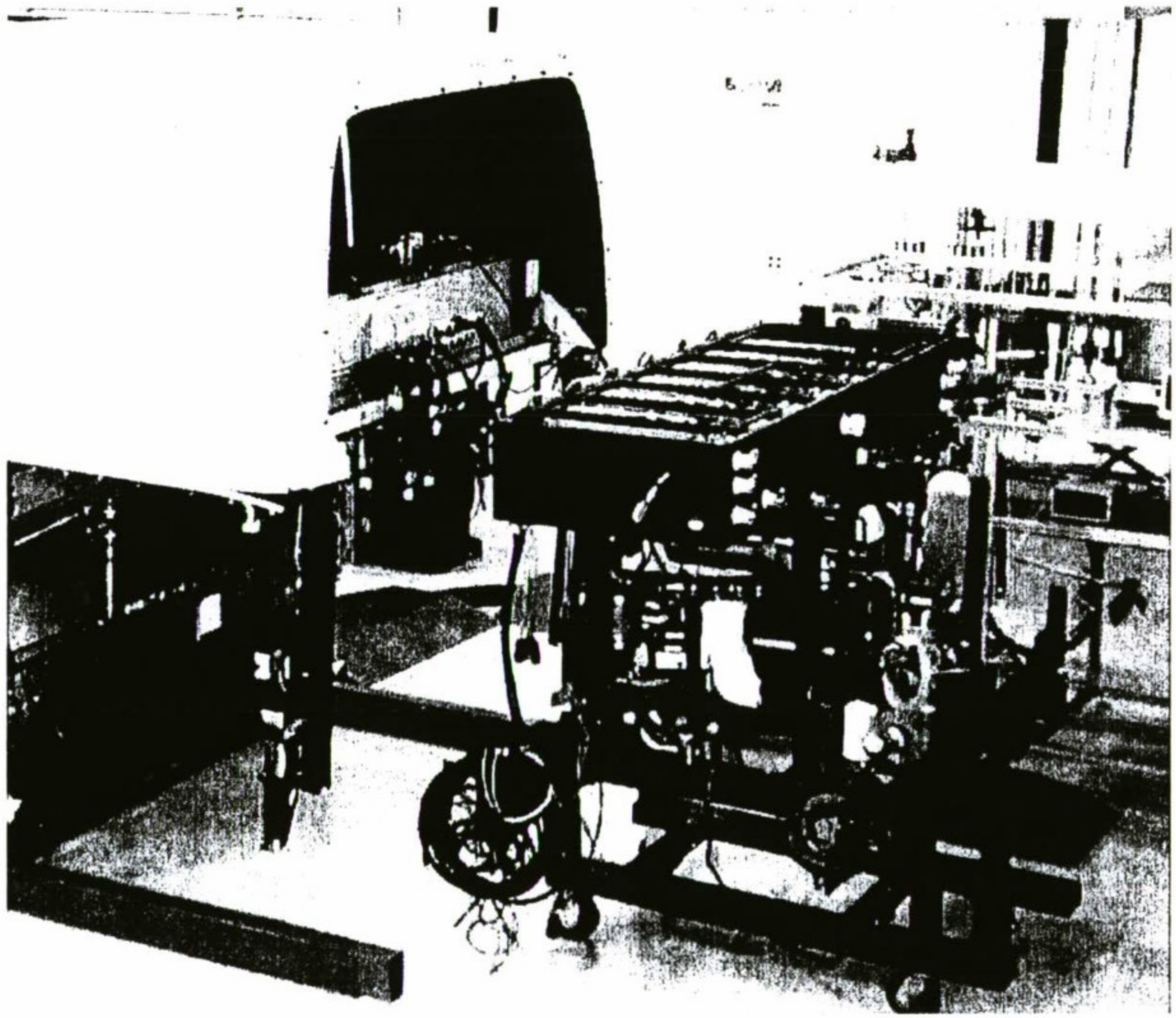
- Extreme temperature operation
- Greater power density may be needed
- Reformer efficiency
- Must use diesel or JP-8 fuel

40-Foot FUEL CELL POWERED TRANSIT BUS

100 kW IFC PAFC POWER PLANT MOUNTED ON BUS



dbb 100 kW PEMFC BUS POWER PLANT



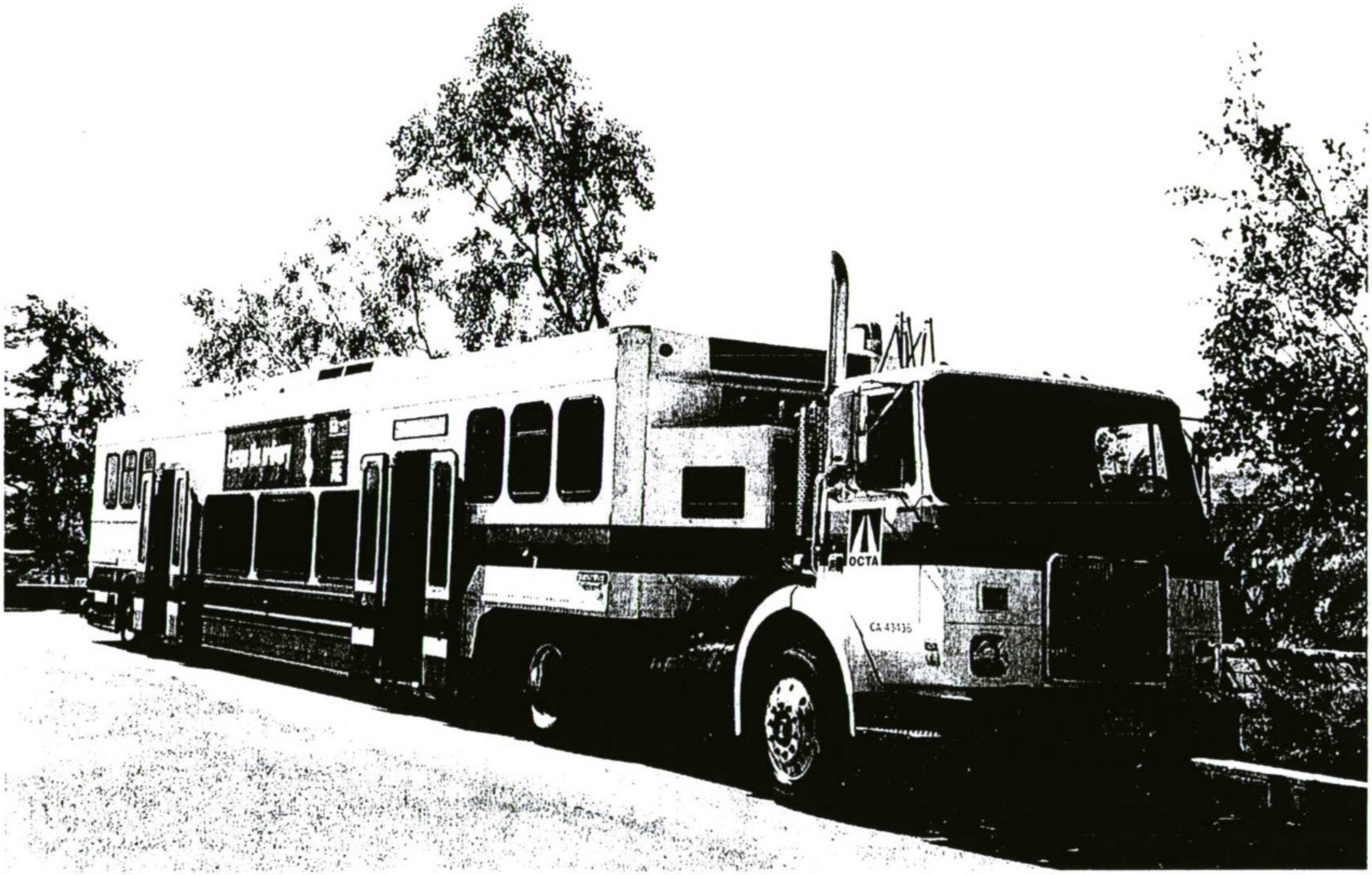
NAC Initiative

Title: Diesel Reformer for a Fuel Cell Powered Line Haul Tractor

Objective: Demonstrate a diesel reformer operating in a PEM fuel cell powered line haul tractor

Schedule: October 1998 to March 2000

SuperBus



SuperBus Cab

Project Team

- National Automotive Center
- SunLine Transit Agency
- University of California-Riverside, College of Engineering - Center for Environmental Research and Technology (CE-CERT)
    - Hydrogen Burner Technology
    - ISE Research
    - The Zeopower Company
- The College of the Desert
- Georgetown University

Program

Phase 1:

- Develop and test reformer
- Develop and install hybrid electric drive system
- Integrate reformer with internal combustion engine power unit on the SuperBus
- Demonstrate reformer as a fuel source for the power unit

Phase 2: (Under 21st Century Truck Program)

- Upgrade reformer
- Integrate PEM fuel cell power unit
- Integrate waste heat-powered air conditioning
- Extended road tests

Emerging Technology

- National Automotive Center
- SunLine Transit Agency
- University of California-Riverside, College of Engineering - Center for Environmental Research and Technology (CE-CERT)
    - Hydrogen Burner Technology
    - ISE Research
    - The Zeopower Company
- The College of the Desert
- Georgetown University

CONTACT

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National Automotive Center
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Warren, MI 48397-5000

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(810) 574-6167 (fax)

dobbsh@tacom.army.mil

Power Electronics & Electric Machines

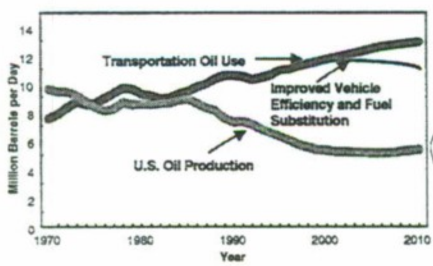
Overview: DOE's Power Electronics and Electric Machines Program

James Merritt
Office of Advanced Automotive Transportation
Office of Transportation Technologies
Energy Efficiency and Renewable Energy
U.S. Department of Energy

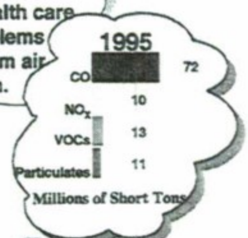
May 4, 1999

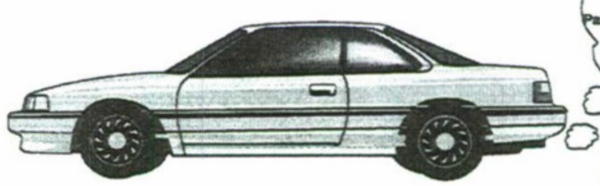
Drivers for Advanced Vehicle Technologies

Power Electronics & Electric Machines



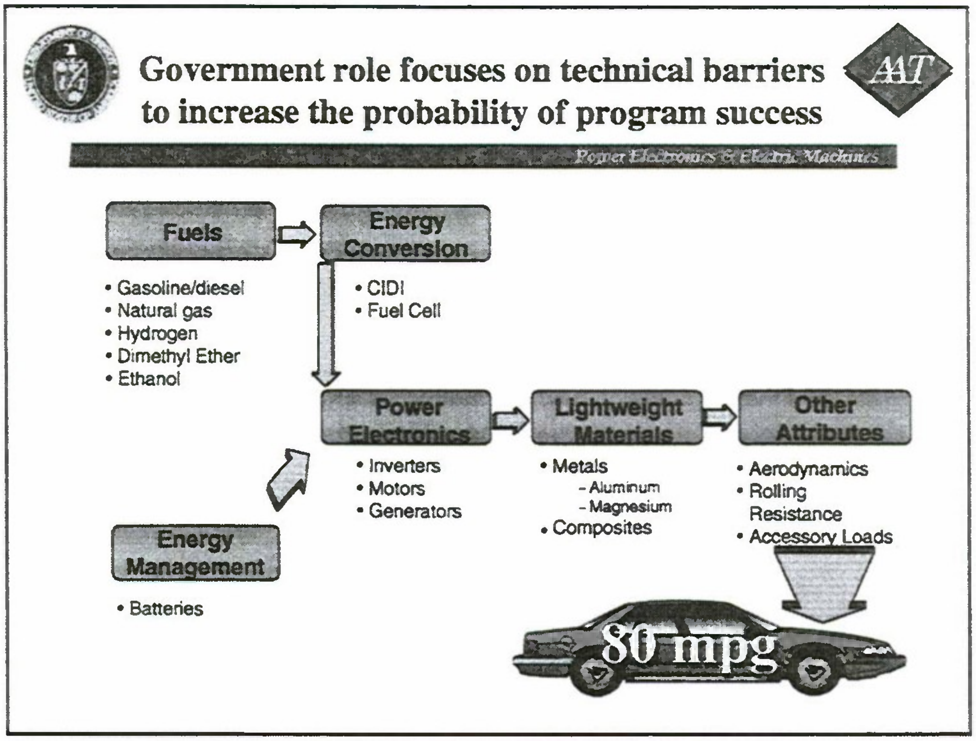
In urban areas, 80% of pollution is attributed to transportation. The American Lung Association estimated in 1988 that Americans spend $50 billion annually on health care to treat problems resulting from air pollution.

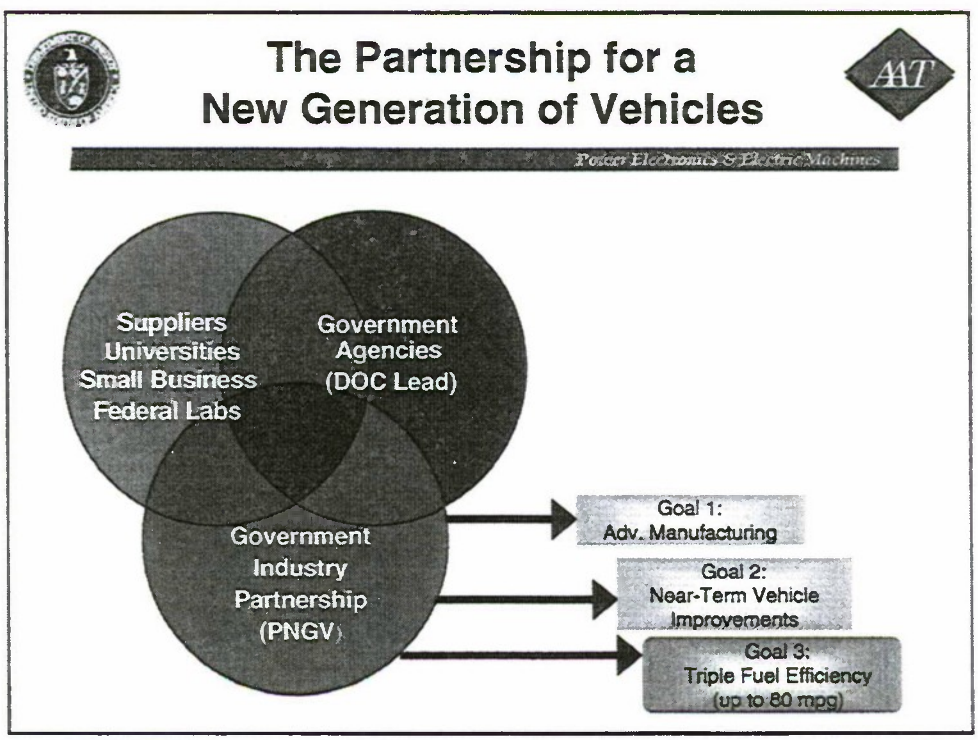




Data also being presented by Tom Gross

Source : EPA


Government role focuses on technical barriers to increase the probability of program success
AAT
Power Electronics & Electric Machines
Fuels
• Gasoline/diesel
• Natural gas
• Hydrogen
• Dimethyl Ether
• Ethanol
Energy Conversion
• CIDI
• Fuel Cell
Power Electronics
• Inverters
• Motors
• Generators
Lightweight Materials
• Metals
- Aluminum
- Magnesium
• Composites
Other Attributes
• Aerodynamics
• Rolling Resistance
• Accessory Loads
Energy Management
• Batteries
80 mpg


The Partnership for a New Generation of Vehicles
AAT
Power Electronics & Electric Machines
Suppliers
Universities
Small Business
Federal Labs
Government Agencies (DOC Lead)
Government Industry Partnership (PNGV)
Goal 1: Adv. Manufacturing
Goal 2: Near-Term Vehicle Improvements
Goal 3: Triple Fuel Efficiency (up to 80 mpg)

Timetable to Achieve PNGV Goal 3

Power Electronics & Electric Machines

1996

Candidates for Development:

- Low emission technologies
- New materials
- Advanced design simulations
- Ultracapacitors and flywheels
- Hybrid vehicles
- Fuel cells, fuel reformers
- Turbines, CIDI engines
- Efficient electronics and electrical devices
- Advanced batteries

Narrow the Technology

2000

Concept Vehicles

2004

Production Prototypes

1997

- ✓CIDI
- ✓Adv. Battery & Electronics
- ✓Fuel Cells
- ✓Materials

Power Electronics: Key Enabling Technology

Power Electronics & Electric Machines

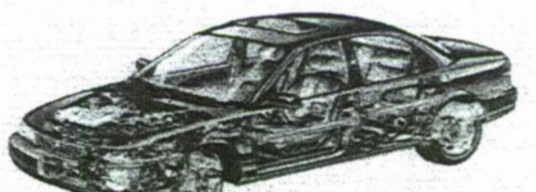
Power Electronics & Motor Applications

Electric Accessories
12V & 42V

Traction Motor & Controller
255V to 450V

Electric Power Steering & Air Conditioning

42V & 350V



Electric Energy Storage Interfaces
42V/150V/350V

Power conditioners and machines for Fuel cells (350V), Generators (42V/150V/350V), ... etc.

Integration of Power Electronics is the key enabling technology for electrification of vehicles

The Logical Transition to Electric Drive

Power Electronics & Electric Machines

An ICE with an 42V, 5kW integral starter/generator, at 40 kW a Light Hybrid.

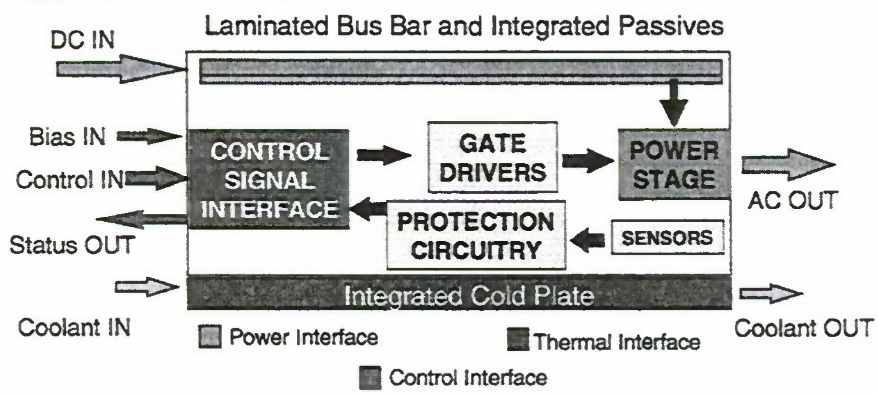
Fuel Cell/EV with a 350V Traction drive system rated at 70kW to 110kW.

Electric A/C & P/S
Options: 35% regeneration to 42V or 150V battery

Electric A/C & P/S
Options: 35% regeneration to 42V or 350V battery

Power Electronic Module

Power Electronics & Electric Machines



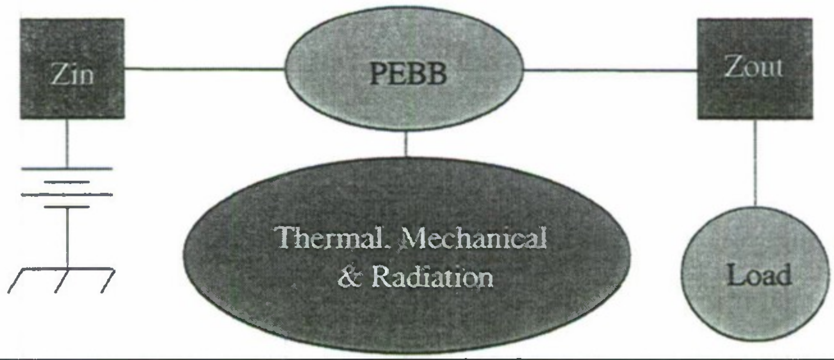
Purpose: to enable cost reduction through up-integration and packaging, in a manner that will allow the module to be used as a standard component.

Power Electronics & Electric Machines

Specifications: The Module Perspective

Power Electronics & Electric Machines

- The module should meet input impedance, voltage and current,
- Load impedance, voltage and current, and
- thermal, mechanical and radiation requirements for automotive applications.



TACOM

Mobility and Firepower for America's Army

Silicon Carbide State of Development

Prof. T. Paul Chow
Rensselaer Polytechnic Institute

Terence Burke
U.S. Army TACOM

Silicon Carbide Power Devices

- Advantages
- Device Development
- Programs and Program Goals
- Basic Performance of Prototype Devices

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Mobility and Firepower for America's Army

Advantages of SiC Power Devices

Superior Material Properties:

Thermal Conductivity (like copper)

High Critical Electric Field (8X Silicon), Wide Bandgap

Lower Switching Losses and Potential for Lower Conduction Losses

Overcomes Thermal Limitations of Silicon Devices

High Temperature Operation 300-500C

High Surge Current

High Frequency at High Power

Very High Voltage Devices

- Smaller: Cooling Systems, Filters, Magnetics
- Switches for Pulsed Power Applications: Electric Guns?

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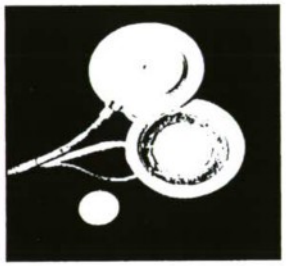
Mobility and Firepower for America's Army

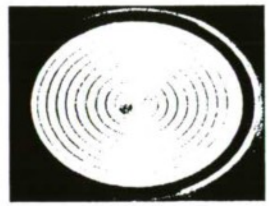
Silicon Carbide Power Device Development

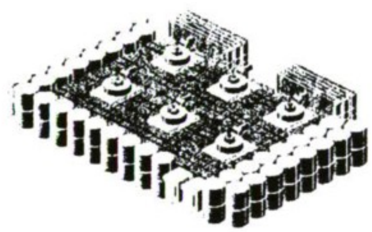
Material

Defects, size
uniformity



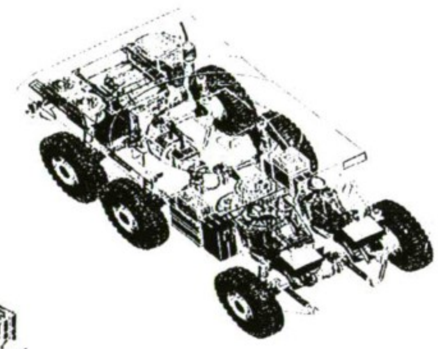
(prototypes)



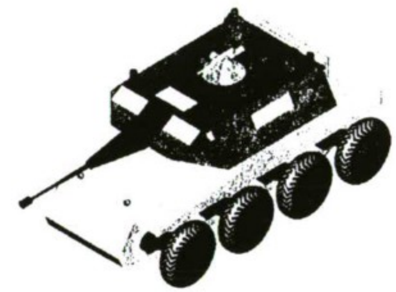


Processing
Fabrication

ion-implantation
etching, dielectric



SIL/demonstrator (CHPS)



ARMY Application

Device Capabilities

some? ---- all ---- + full power

CW/Pulsed?

Power Converter

basic, small ------ advanced, full-power

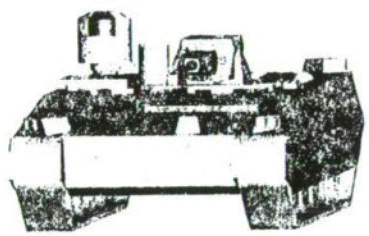
1990 **1995** **2000** **2005** **2010** **2025**

Commercialization?

TACOM

Mobility and Firepower for America's Army

SiC Programs



- DARPA CHPS
- DARPA/EPRI MW Electronics:
  P.M.: Dr. Raddack:
  GE, RPI, Northrop Grumman, NASA, SPCO, Universities
- STO with ARL for 1kV, 400C SiC GTO and JFET
- Phase I SBIR with United SiC for MPS Diodes

- PEBB Program: 2002 - High Temp, 2005 - 40kV PEBBS
- ONR MURI Program, "Robust, Wide Bandgap Power Switching"
  Purdue, RPI, U.T. Austin, Howard, Cree Research
- DARPA/ONR Diode Program

- DARPA/Air Force 4H-SiC Materials
- Title III "SiC Substrates" (Aug 99)
  - J. Blevins, AFRL
- Phase II SBIR with Cree Research ACCUFET and 600V Schottky
- DARPA TRP3 for SiC GTO, Diodes

- DOD Title III Program (FY 98): includes SiC GTO/MTO "Power Switching Devices" with SPCO (R. Andraca) C. Severt (AFRL), G. Campisi (NRL), H. Singh (ARL)

Basic Performance of SiC Prototype Devices

Material: Cree Research reports (Dec. '98) micropipe reduction in production 4H-SiC
1 3/8" diameter, <10 cm^{-2}; 2" diameter, 15 cm^{-2}

Schottky Rectifiers:

Cree Research: 8mm x 8mm, **300V** reverse blocking, **130A** @200A/cm^2, V_f 3.25V. Projected packaged 70 amps at V_f 2.5V
6mm x 6mm goes to 600V with V_f 3.2V at 35A

Purdue: 1700V Ni: 4H-SiC (note: Vb^2/Ron within 4x of SiC limit)

PiN Rectifiers: Cree Research 5.5kV, V_f 6.5V at 2A

MOSFETS: 2.6 kV lateral DMOS (Purdue)
1.4kV UMOS ACCUFETs with Vb^2/Ron 25x higher than Si limit but 16x lower than SiC limit (theoretical)

IGBT: Cree Research reports -85V blocking, -30mA with 28-30V threshold

Thyristor: 700V 4H-SiC, 6A V_f 3.7V at 1000A/cm^2

GTO: Rutgers University reports turn-off at 10,000A/cm^2, (to 160V) with a turn-off current gain of about 3; 800V blocking.

Harris (G. Dolny): measured 4x lower IGBT turn-on losses when a SiC Schottky replaces a silicon pin diode (300V, 6A, 340 A/us) in clamped-inductive test

Recent Advances in SiC High-Voltage Power Devices

T. Paul Chow

Rensselaer Polytechnic Institute

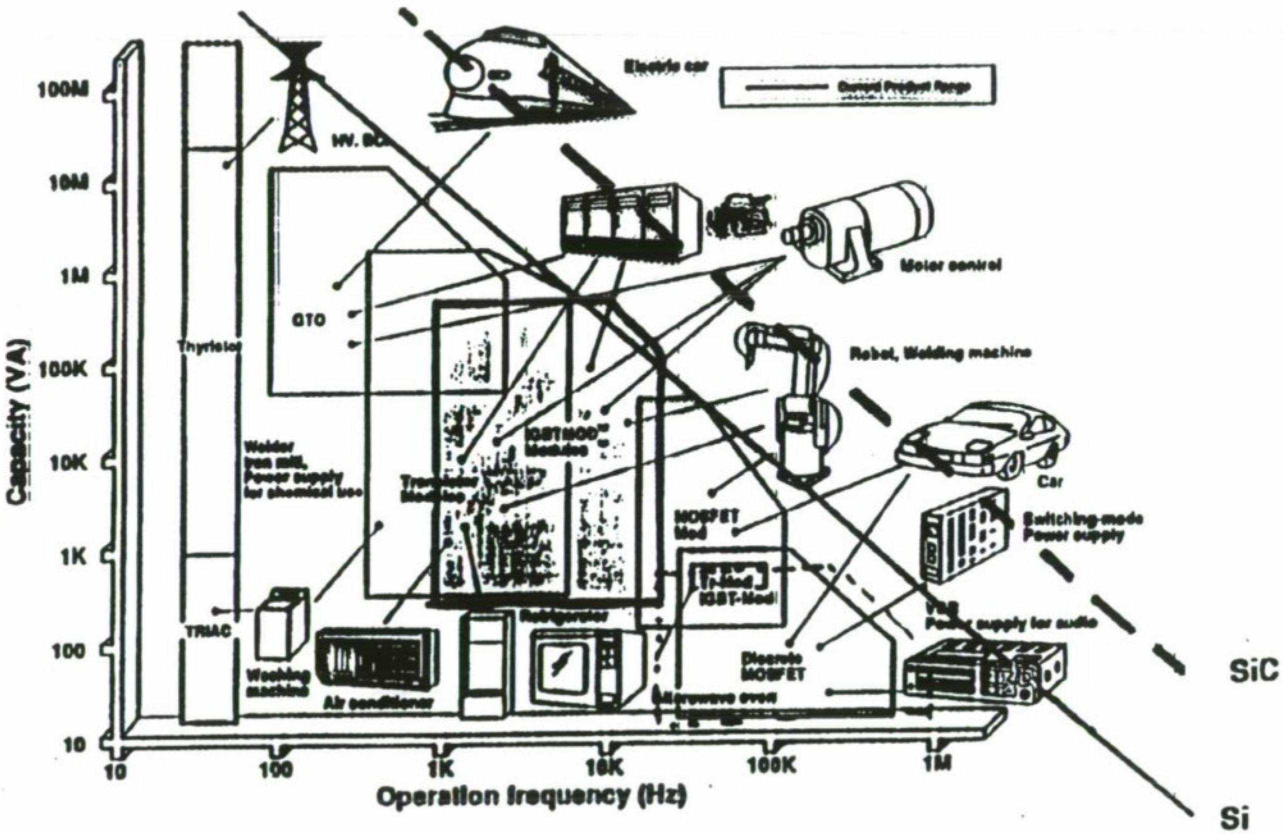
Troy, NY 12180-3590

e-mail: chow@unix.cie.rpi.edu

Outline

- Introduction
- Figures of Merit
- Device Structures
- Performance Potentials
- Recent Experimental Results
- Materials and Process Challenges
- Summary

Application of Power Devices



Modified from an Application Note of Powerex, Inc.,Youngwood, PA

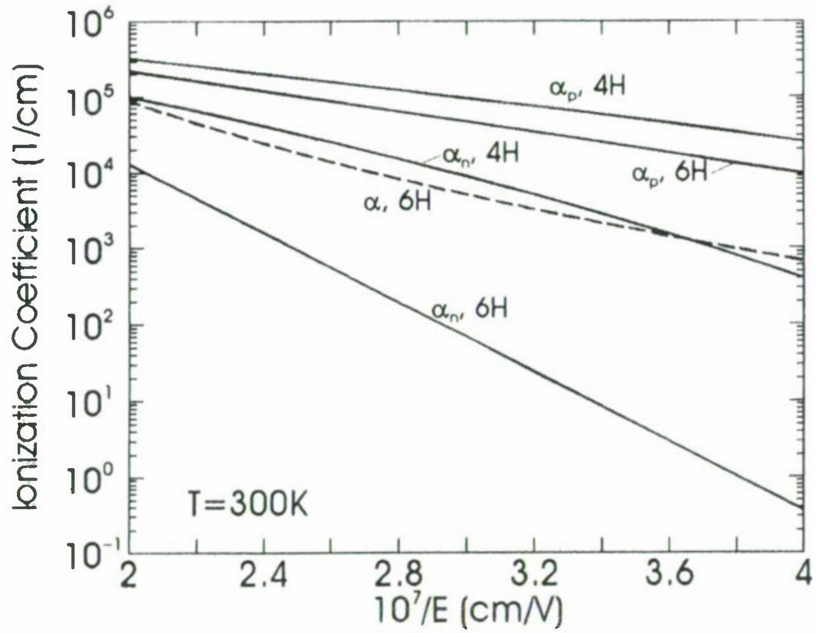
Material Properties

Material	E_g eV	ε_r	μ_n $cm^2/V\cdot s$	E_c 10^6 V/cm	v_{sat} 10^7 cm/s	λ $W/cm\cdot K$	n_i cm^{-3}
Si	1.1	11.8	1350	0.3	1.0	1.5	1.5×10^{10}
Ge	0.66	16.0	3900	0.1	0.5	0.6	2.4×10^{13}
GaAs	1.4	12.8	8500	0.4	2.0	0.5	1.8×10^{6}
GaP	2.3	11.1	350	1.3	1.4	0.8	7.7×10^{-1}
GaN	3.39	9.0	900	3.3	2.5	1.3	1.9×10^{-10}
3C-SiC	**2.2**	**9.6**	**900**	**1.2**	**2.0**	**4.5**	**6.9**
4H-SiC	**3.26**	**10**	**720^a 650^c**	**2.0**	**2.0**	**4.5**	**8.2×10^{-9}**
6H-SiC	**2.86**	**9.7**	**370^a 50^c**	**2.4**	**2.0**	**4.5**	**2.4×10^{-5}**
Diamond	5.45	5.5	1900	5.6	2.7	20	1.6×10^{-27}
AlN	5.61	8.7	1100	1.2	1.8	1.7	

Note: *a* — mobility along a-axis, *c* — mobility along c-axis

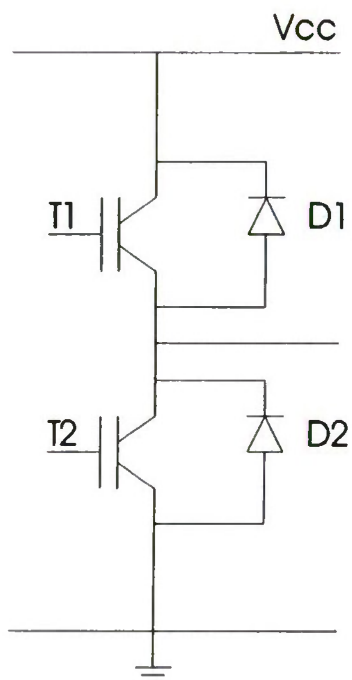
Availability?
Reproducible single-crystal wafers?
Processing Technology Feasible?

SiC Ionization Coefficients



- Experimental extraction of impact ionization coefficients from pn and Schottky junction breakdown has been performed.
- In contrast to Si, $\alpha_p > \alpha_n$ in both 6H- and 4H-SiC

Introduction



2-Terminal Devices:
- Schottky Rectifiers
- Junction Rectifiers
- JBS/MPS

3-Terminal Devices:
- MOSFETs
- IGBTs
- GTOs

Unipolar Figure of Merits

Material	JM	KM	Q_{F1}	Q_{F2}	BM (Q_{F3})	BHFM
	$(E_c v_{sat}/\pi)^2$	$\lambda(v_{sat}/\varepsilon_r)^{1/2}$	$\lambda\sigma_A$	$\lambda\sigma_A E_c$	$=\sigma_A \propto \varepsilon_r \mu E_c^3$	μE_c^2
Si	1	1	1	1	1	1
Ge	0.03	0.20	0.06	0.02	0.2	0.3
GaAs	7.1	0.45	5.2	6.9	15.6	10.8
GaP	36.8	0.65	10.2	44.2	19.1	4.7
GaN	760	1.6	560	6220	650	77.8
3C-SiC	65	1.6	100	400	33.4	10.3
4H-SiC	180	4.61	390	2580	130	22.9
6H-SiC	260	4.68	330	2670	110	16.9
n-Diamond	2540	32.1	54860	1024000	4110	470

Basic Considerations: Thermal Properties of material (both generation and evacuation)

Bipolar Figure of Merits

*IGBT : Dependence on Materials**

J_F=100A/cm^2, V_{BR}=1000V

Material	N_d (cm^{-3})	W_{N^-} (μm)	W_R (μm)	α_{PNP}	τ_{n0} (μs)	V_F (V)	J_{OFF} (A/cm^2)	τ_B (μs)	E_{OFF} (mJ)	f_{min} (kHz)
Si	1.3e14	100	6	0.14	1.0	1.2	2.0e-5	0.285	2.55	-
Ge	4.4e13	200	12	0.14	0.95	0.63	8.5e-2	0.302	2.70	<190
3C-SiC	3.8e15	16.7	1	0.14	0.37	2.74	5.4e-15	0.058	0.55	38.4
6H-SiC	1.6e16	8.3	0.5	0.14	0.15	2.97	1.8e-20	0.016	0.15	36.9
Diamond	1.2e17	2.3	0.14	0.14	0.0011	5.04	5.0e-41	0.6e-4	0.5e-3	75.3

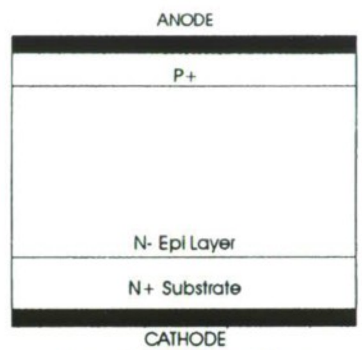
Note:

W_R : Required width of the JFET region. Lower W_R allows increased channel density.

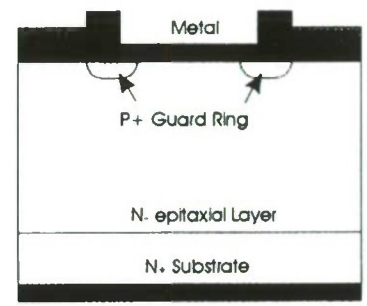
τ_B : Base transit time

* From: A. Bhalla, T.P. Chow, "*Bipolar Power Device Performance: dependence on material, lifetime, and device rating*", Proc. of 6th ISPSD, pp. 287-292, 1994

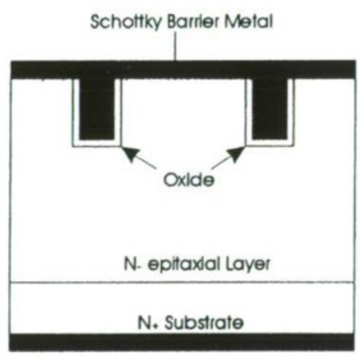
Two-Terminal Devices



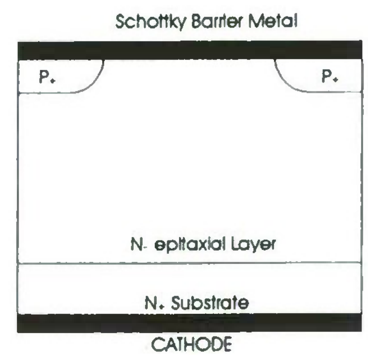
Junction Rectifier



Schottky Rectifier

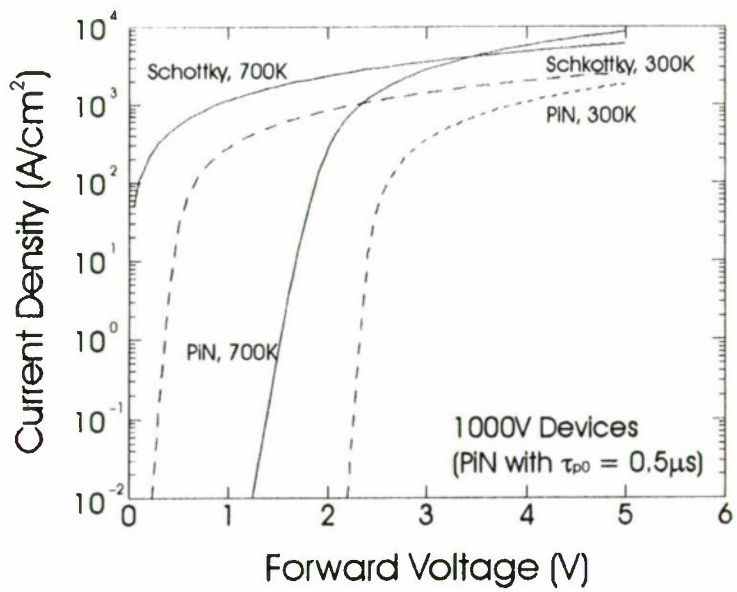


MBS Rectifier

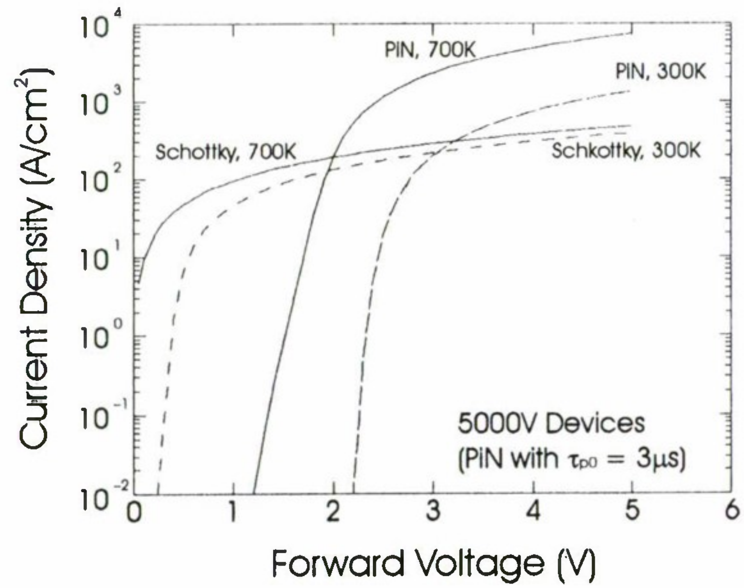


JBS/MPS Rectifier

Forward I-V Characteristics



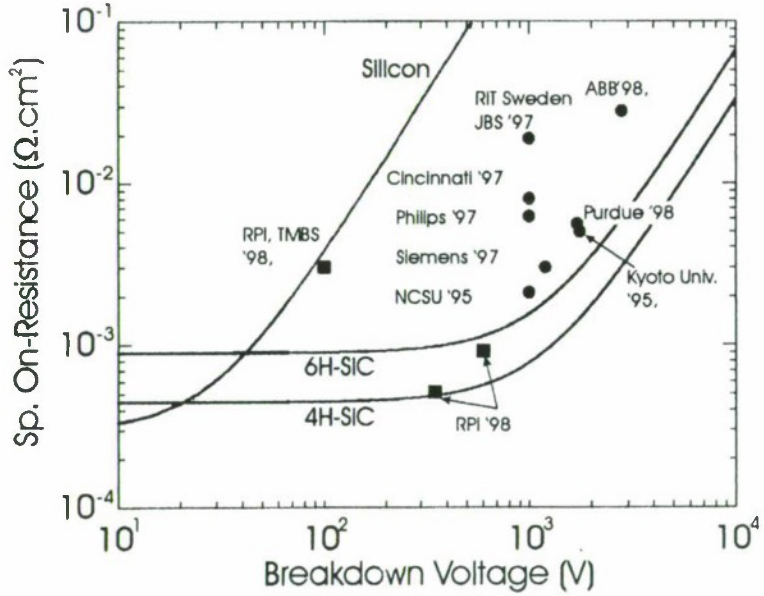
Forward I-V Characteristics of 1000V SiC PiN and Schottky Rectifiers



Forward I-V Characteristics of 5000V SiC PiN and Schottky Rectifiers

Schottky Diodes

- Attractive due to fast switching speed
- Simple structure least affected by material imperfections
- Leakage currents high in SiC Schottky diodes
- Nickel and Titanium are common Schottky metals
- Surface cleaning important

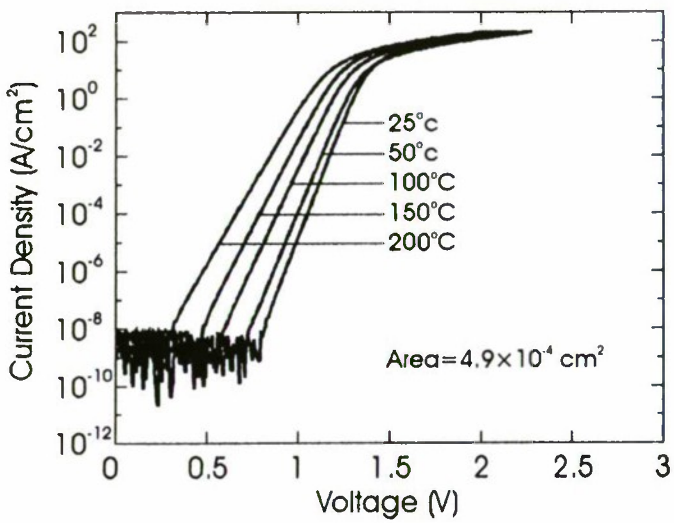


$$R_{on} = R_d + R_{sub} = (4BV^2/\mu\varepsilon E_c^{\,3}) + \rho_{sub}W_{sub}$$

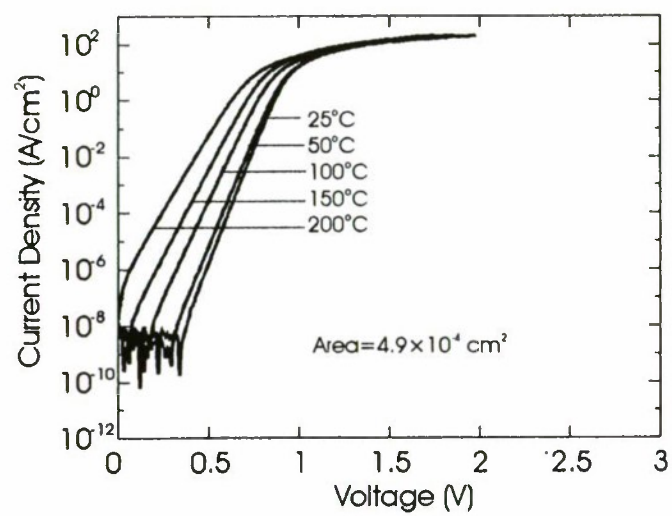
Schottky Diodes

Forward Characteristics

Ni/4H-SiC

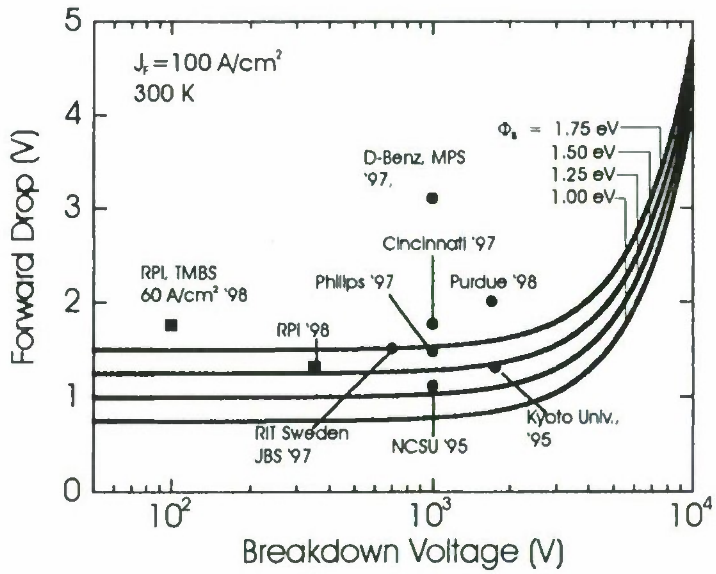


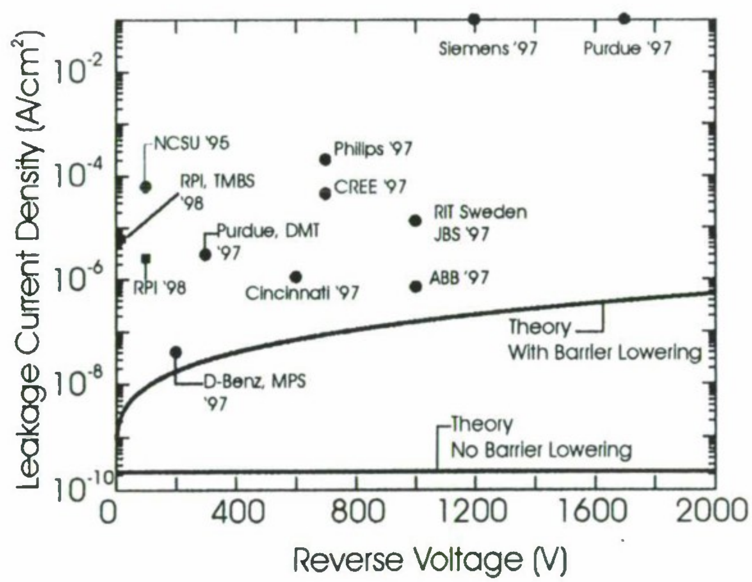
Ti/4H-SiC



- Barrier height (ϕ_B): Ni ~ 1.7 eV and Ti ~ 1.3 eV
- Ideality factor (n): Ni ~ 1.03 and Ti ~ 1.03
- Richardson's Constant: 140 A/cm^2.K^2

Schottky Diodes

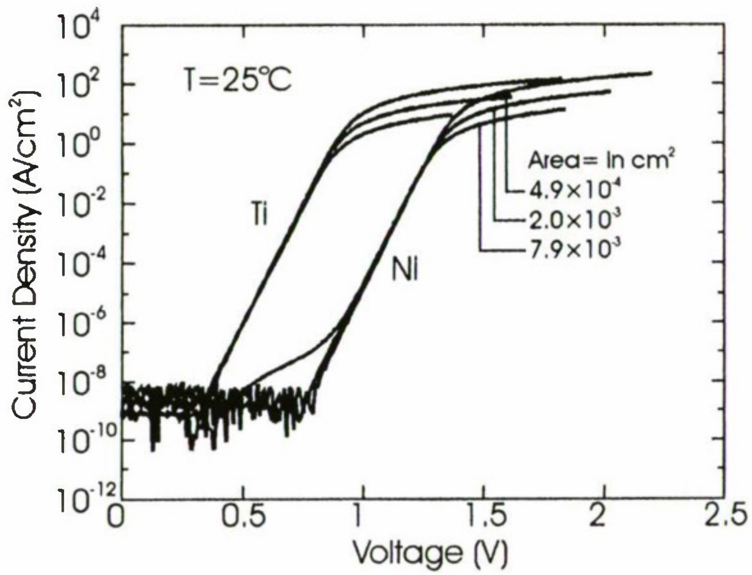


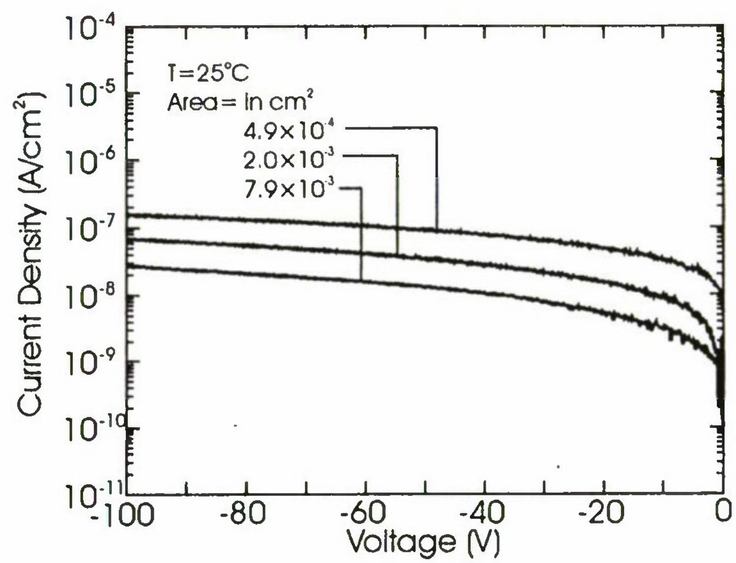


- Experimentally reported results on SiC Schottky are well short of their theoretical predictions
- Material quality and surface conditioning play an important role

Schottky Diodes

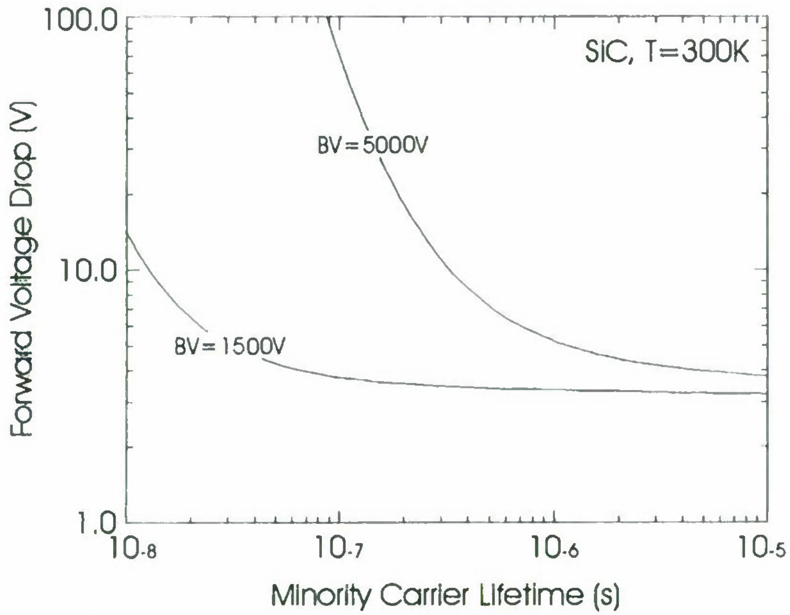
Effect of Device Area



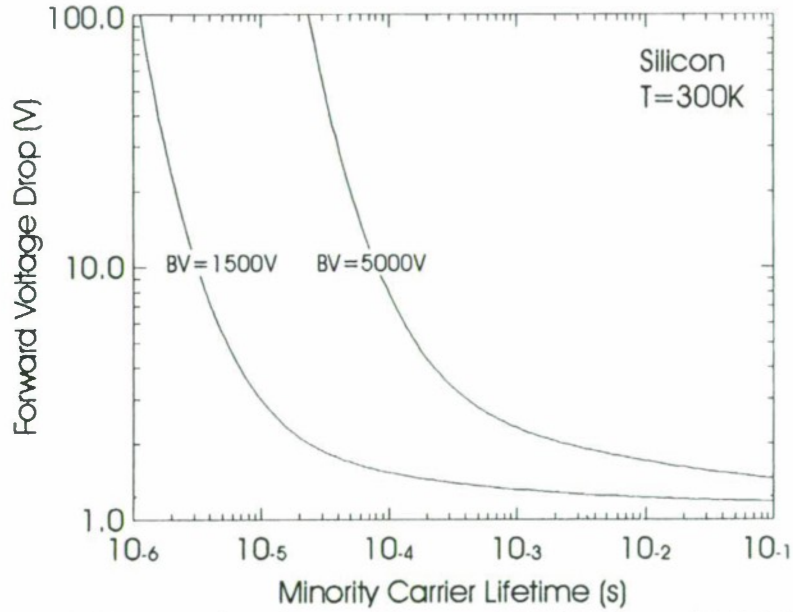


- Forward characteristics scale with area only in the exponential region
- Reverse characteristics does not scale with area: perimeter dominated reverse leakage current

Junction Rectifiers: Trade-off Curve

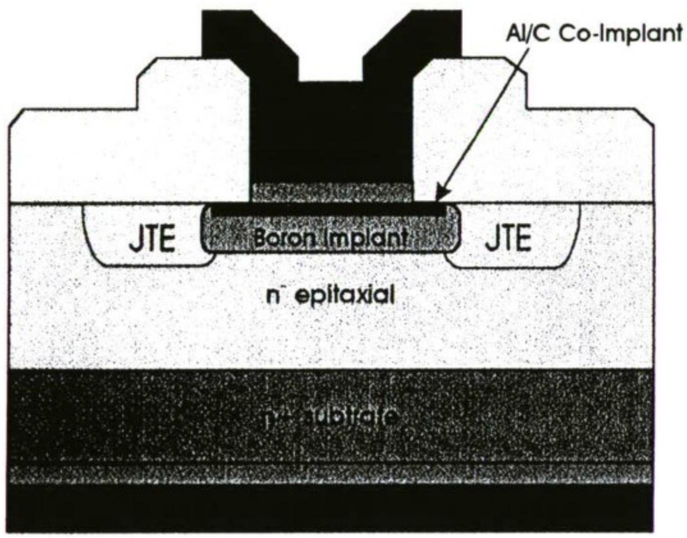


Forward voltage drop of 1500V and 5000V 4H-SiC PiN rectifiers as a function of minority carrier lifetime (J_F=100A/cm$_2$).



Forward voltage drop of 1500V and 5000V Si PiN rectifiers as a function of minirity carrier lifetime (J_F=100A/cm$_2$).

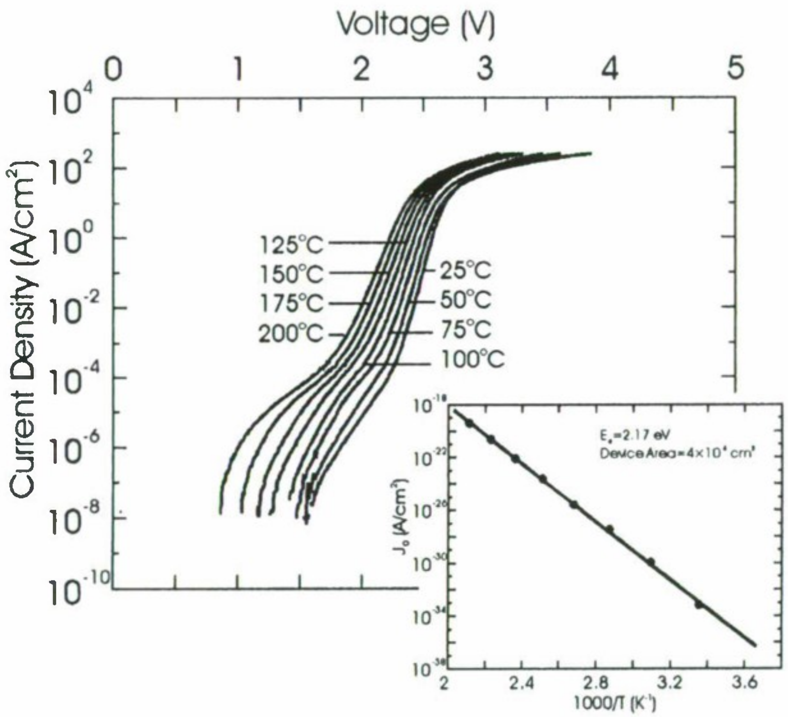
Double-Implanted PiN Rectifier

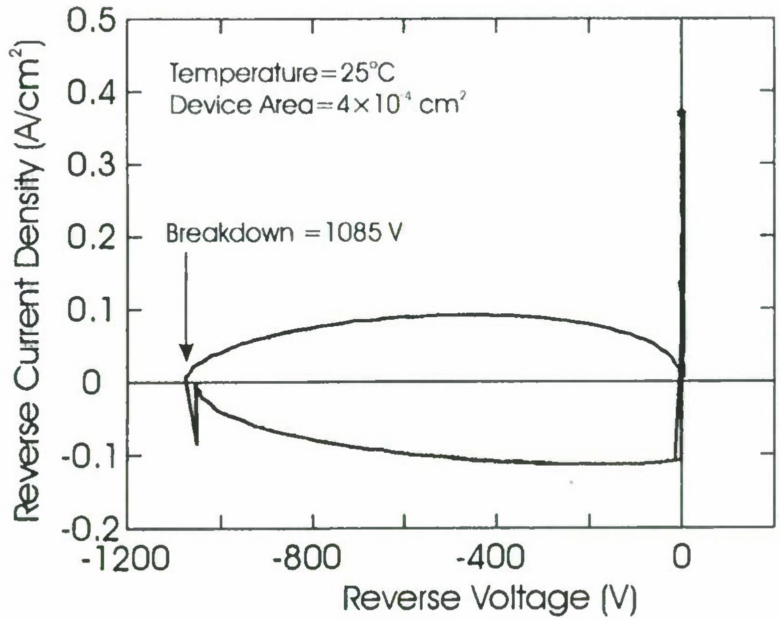


- Drift Layer Thickness: 10 - 40 μm
- Drift Layer Doping: 2×10^{15} - 2×10^{16} cm^{-3}
- Boron Implant Emitter (cm^{-2}: KeV): 1.5×10^{15}:195, 6.2×10^{14}:165, 6.5×10^{14}:135, and 7.2×10^{14}:105
- Al/C Co-implanted shallow layer (cm^{-2}: KeV): Aluminum:2.5×10^{15}:175, 1.4×10^{15}:90, 7.0×10^{14}:40 and Carbon: 2.5×10^{15}:85, 1.4×10^{15}:40, 7.0×10^{14}:20
- Boron Implant for JTE (cm^{-2}: KeV): 7.0×10^{12}:360, 3.0×10^{12}:250, 4.0×10^{12}:180, and 6.0×10^{12}:100.
- Anneal cycle: 1650°C, 30 min.
- Breakdown Voltage: 1100 - 4500 V

Hall Measurement of Al/C co-implanted layer:
Mobility ~ 7 cm^2/V.s, Activation < 1%

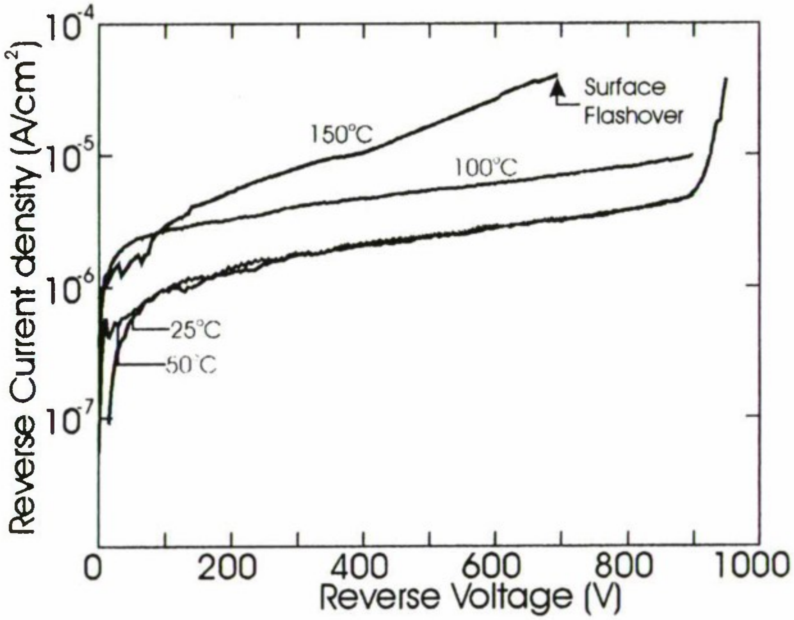
Double-Implanted PiN Rectifier

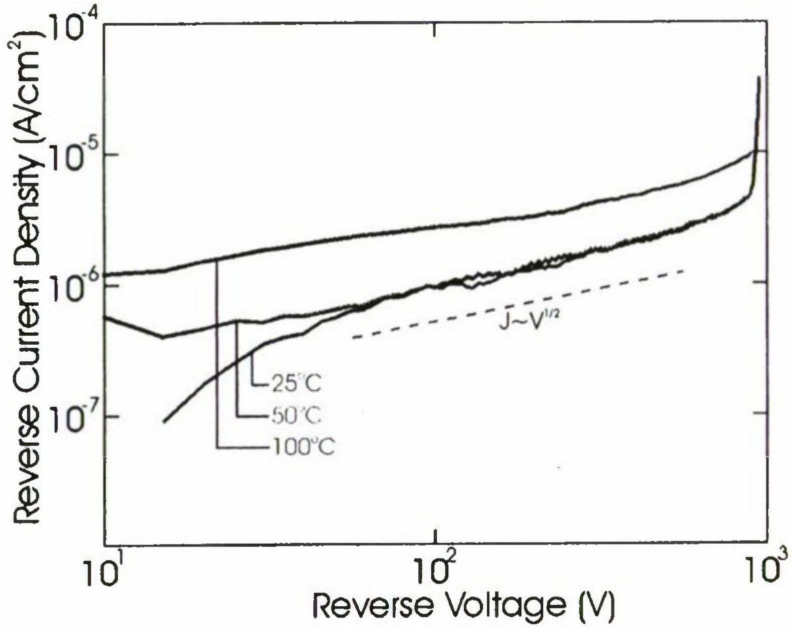




Double-Implanted PiN Rectifier

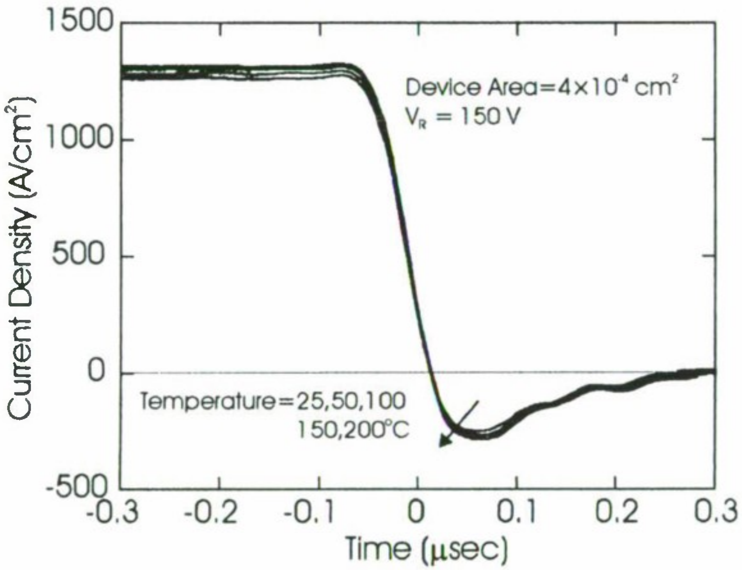
Reverse Characteristics

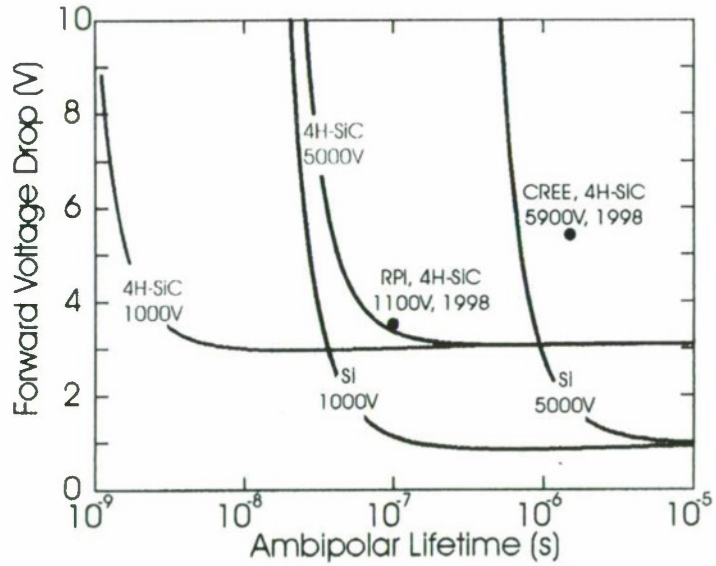




- Leakage current varies as square root of the reverse voltage indicating generation current
- However, surface and periphery currents still seem to be dominant

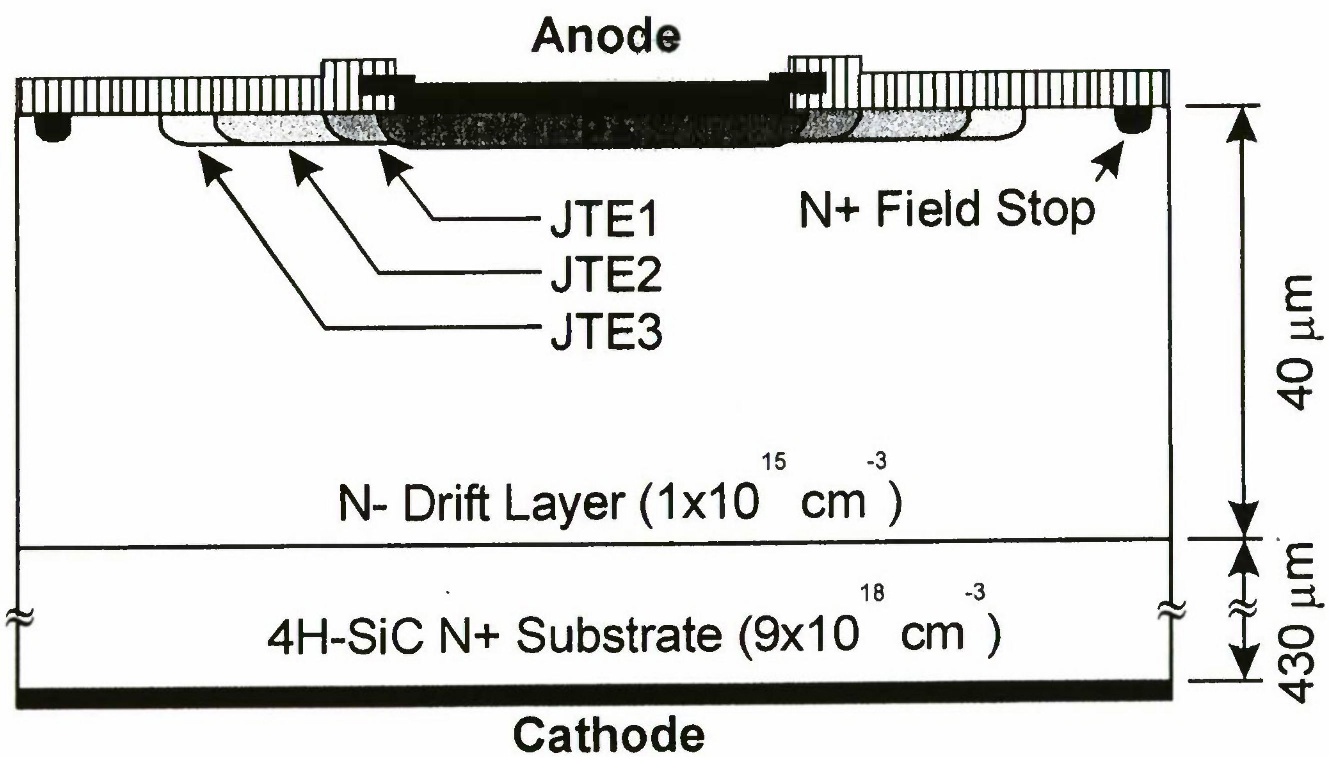
Trade-off in PiN Rectifiers



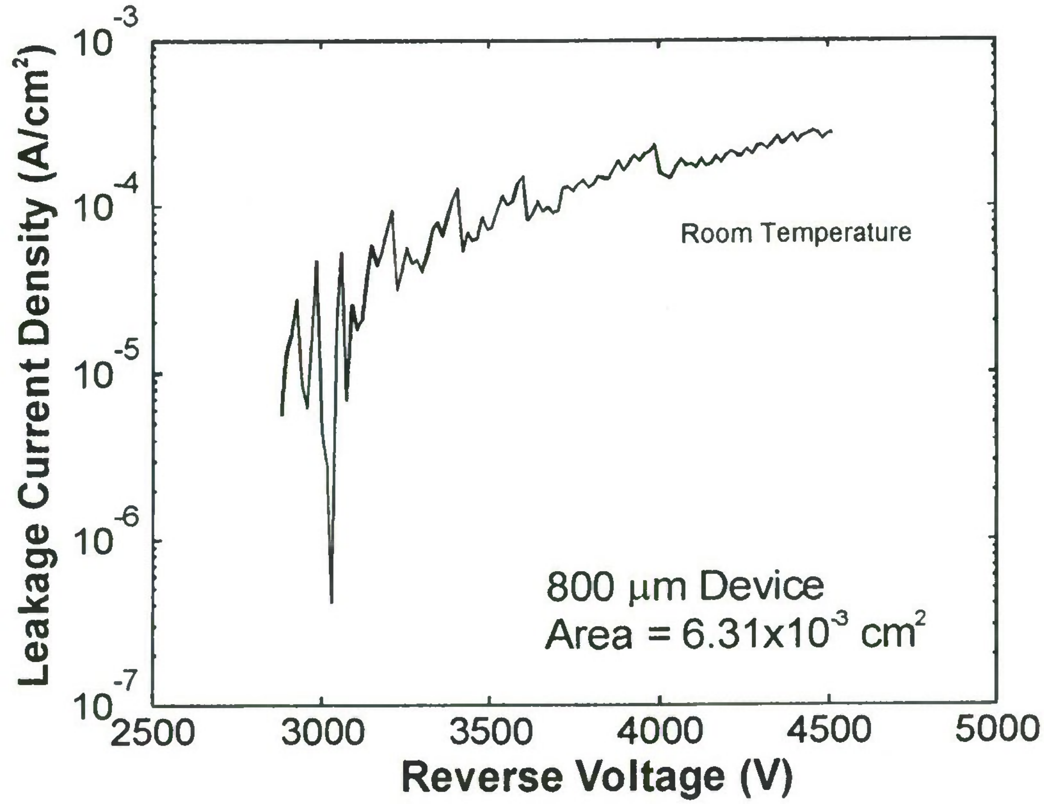


- RPI'1998: Boron/Al-C Double-Implanted 1100 V PiN Rectifier, 10 μm, 1.8×10^{16} cm^{-3} n/n^+ epi
- CREE'1998:Epitaxial, 5900 V, PiN Rectifier, 85 μm, $1\text{-}7\times10^{14}$ cm^{-3} n/n^+ epi

4H-SiC p-i-n Diode Structure Designed For 5kV Blocking



4500V Double-Implanted Pin Rectifier



4500V Double-Implanted Pin Rectifier

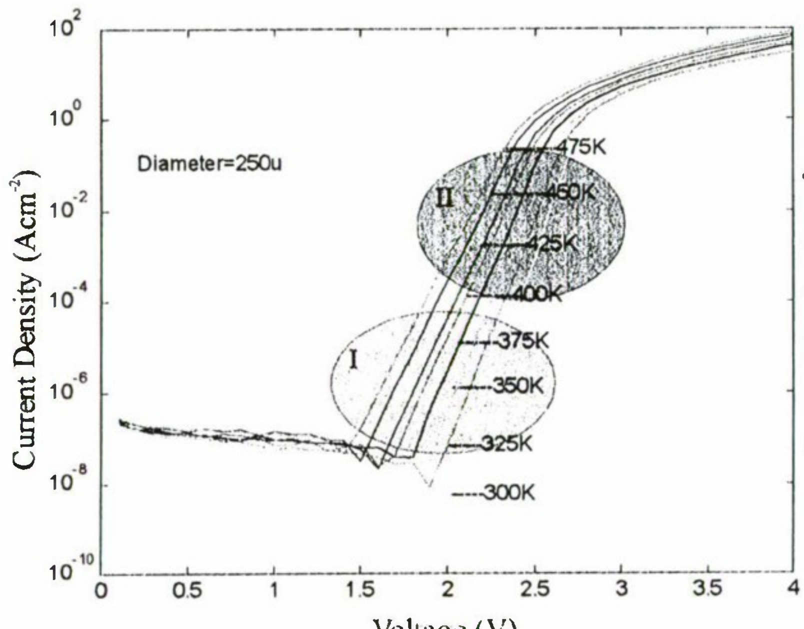


Fig. 1 AB0264-08 250uDiode Forward J-V Curve

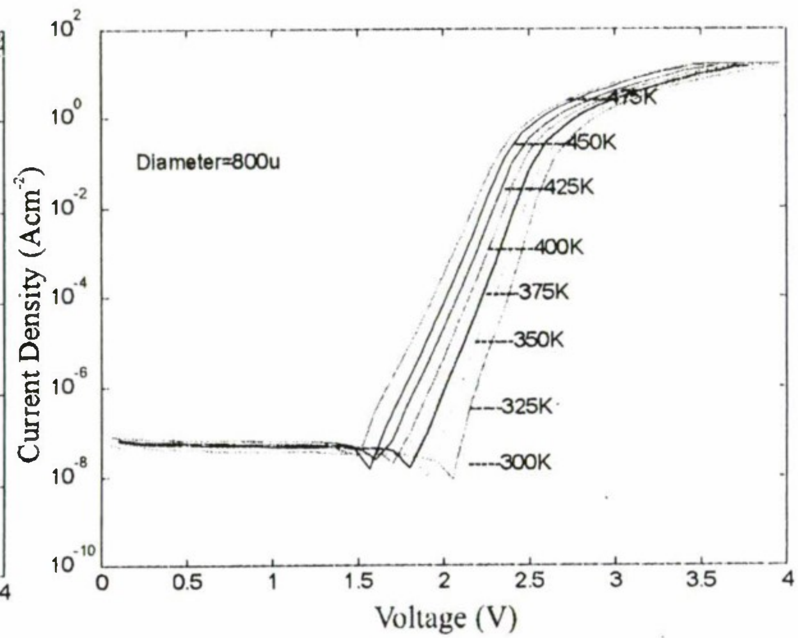
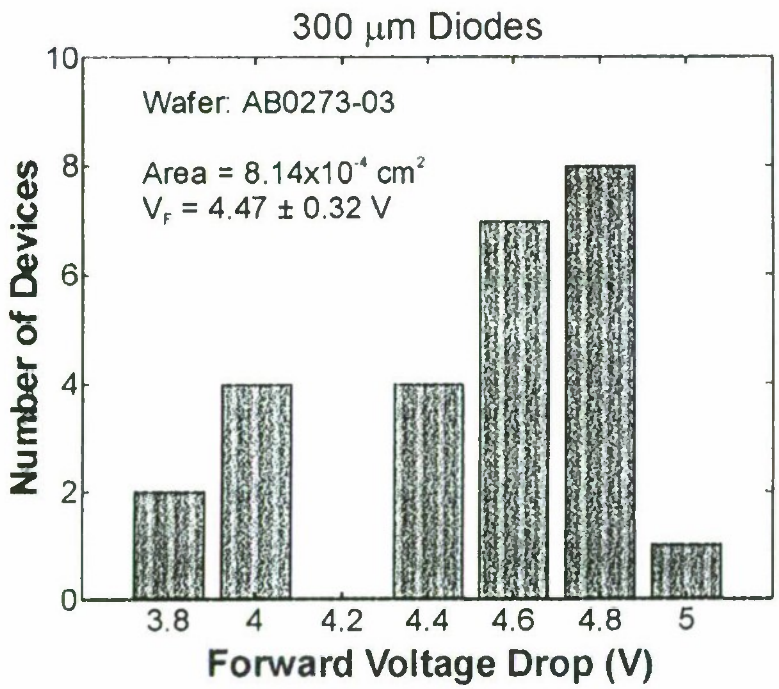
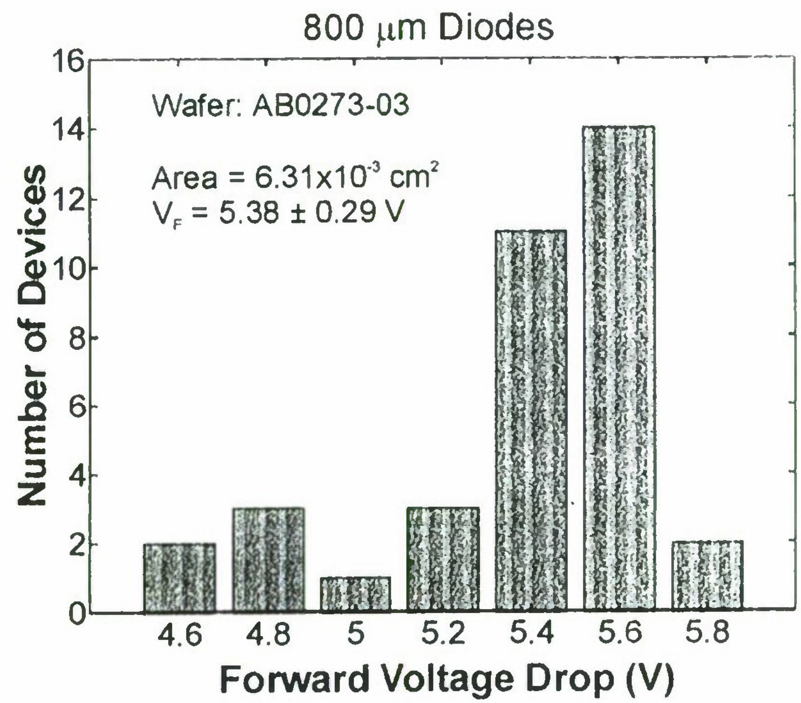


Fig. 2 AB0264-08 800uDiode Forward J-V Curve

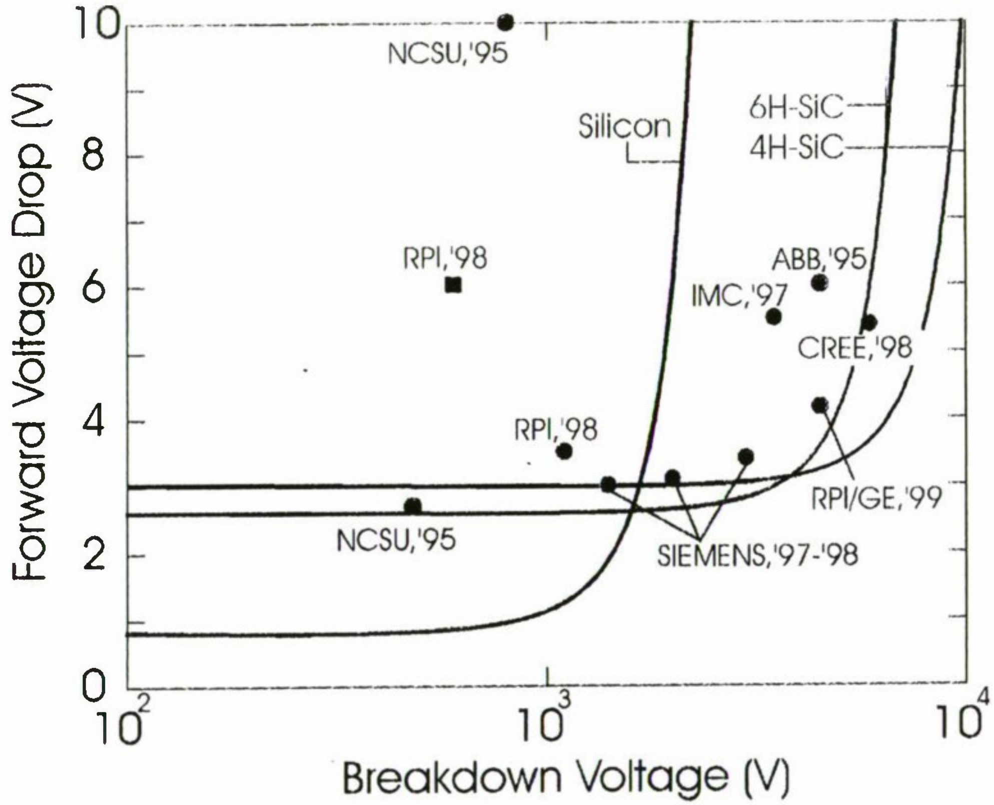
4500V Double-Implanted Pin Rectifier

Forward Voltage Drop at 100 A /cm^2



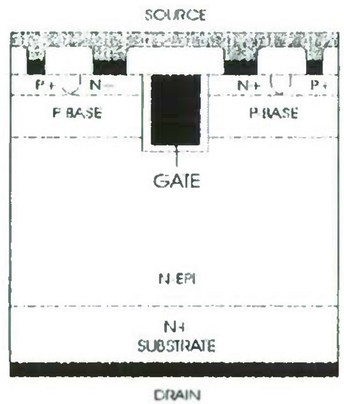


Trade-off in PiN Rectifiers

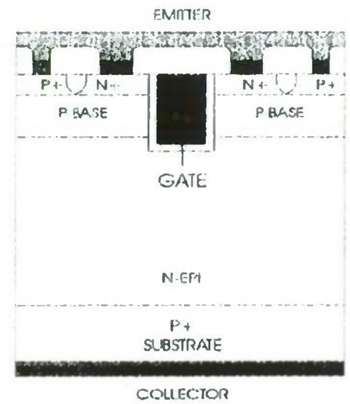


- Highest reported breakdown voltage ~ 5900V by CREE with a V_F~5.6V at 100 A/cm^2, 85μm, n/n^+ epi
- Highest breakdown voltage achieved by RPI/GE ~ 4500V with a V_F~4.2V at 100 A/cm^2, 40μm, n/n^+ epi

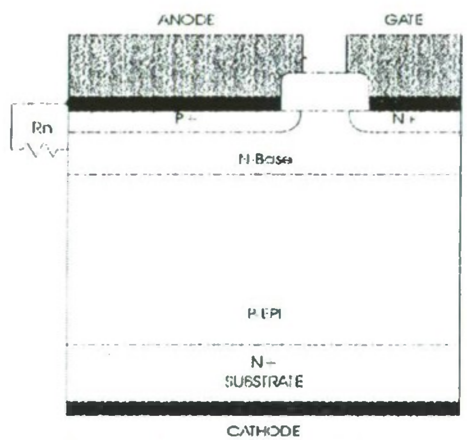
Three-Terminal Devices



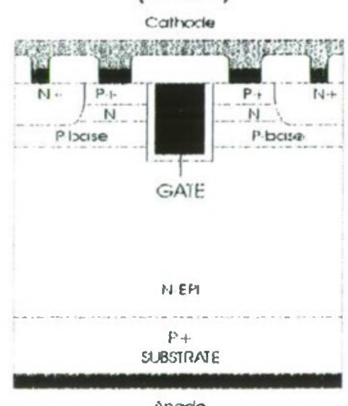
MOSFET



Insulated Gate Bipolar Transistors (IGBTs)



Gate Turn-Off Thyristors (GTOs)

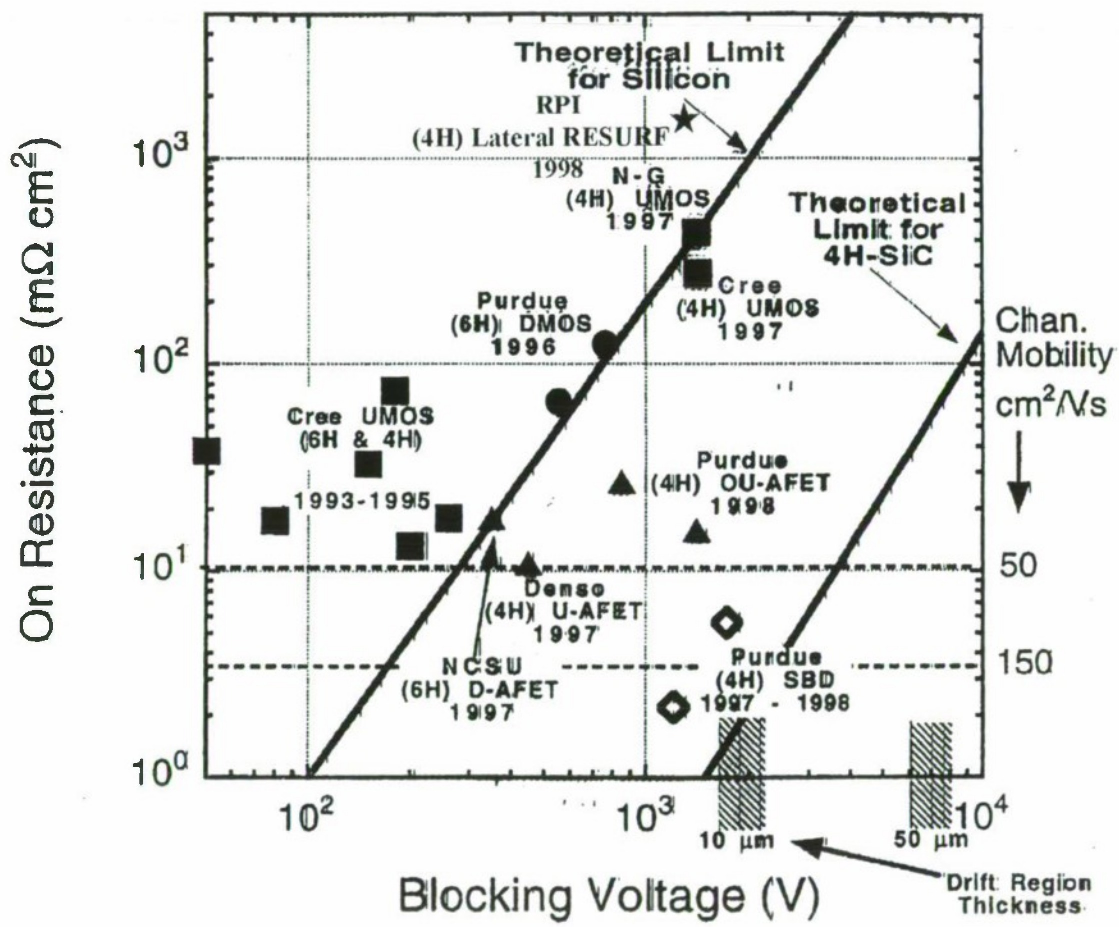


MOS-Controlled Thyristors (MCTs)

Recent Demonstrations of SiC High-Voltage Transistors

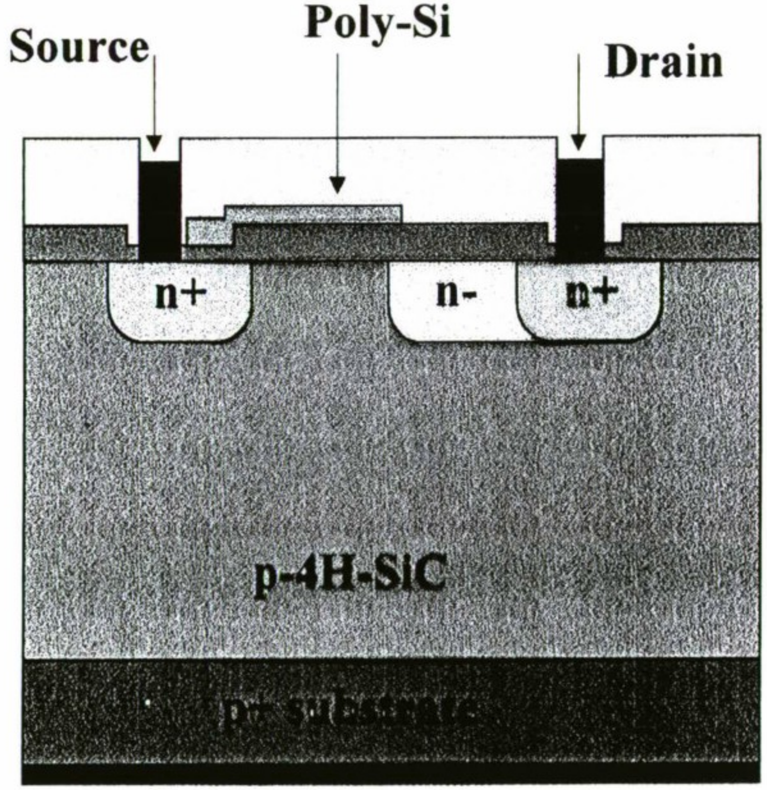
Device Type	Polytype	Power Ratings	Features	Researcher
MOSFET	6H-SiC	60V, 125mA	UMOS, $38m\Omega \cdot cm^2$	Cree, 1993
	4H-SiC	150V, 150mA	UMOS, $33m\Omega \cdot cm^2$	Cree, 1993
	4H-SiC	260V, 100mA	UMOS, $18m\Omega \cdot cm^2$	Cree, 1995
	4H-SiC	1100V	UMOS, $74m\Omega \cdot cm^2$ @100°C	Northrop Grumman, 1997
	4H-SiC	1400V	UMOS, $311m\Omega \cdot cm^2$	Kansai Elec., 1998
	6H-SiC	760V, 3mA	DMOS, $125m\Omega \cdot cm^2$	Purdue U., 1996
	4H-SiC	900V	DMOS, ? $m\Omega \cdot cm^2$	Northrop Grumman, 1997
	4H-SiC	550V, 1A	DMOS, $25m\Omega \cdot cm^2$	Siemens, 1997
	4H-SiC	2.6kV, 1µA	Lateral DMOS	Purdue U., 1997
	4H-SiC	450V, 100mA	Accumulation mode FET, $11m\Omega \cdot cm^2$	Denso, 1997
	6H-SiC	350V, 100mA	Accumulation mode FET, $18m\Omega \cdot cm^2$	N. Carolina SU, 1997
	4H-SiC	450V, 5mA	Accumulation mode FET, $3.2\ \Omega \cdot cm^2$	N. Carolina SU, 1998
	4H-SiC	850V, 25mA	Accumulation mode FET $27m\Omega \cdot cm^2$	Purdue U., 1998
BJT	6H-SiC	200V, 20mA	$\beta \sim 10$, $126m\Omega \cdot cm^2$	Cree, 1993
IGBT	6H-SiC	200V, 1mA	Self-Aligned UMOS	RPI/GE, 1996
	4H-SiC	800V	Self-Aligned UMOS, p-channel	RPI, 1997

Performance of SiC
Power MOSFETs and Schottky Diodes

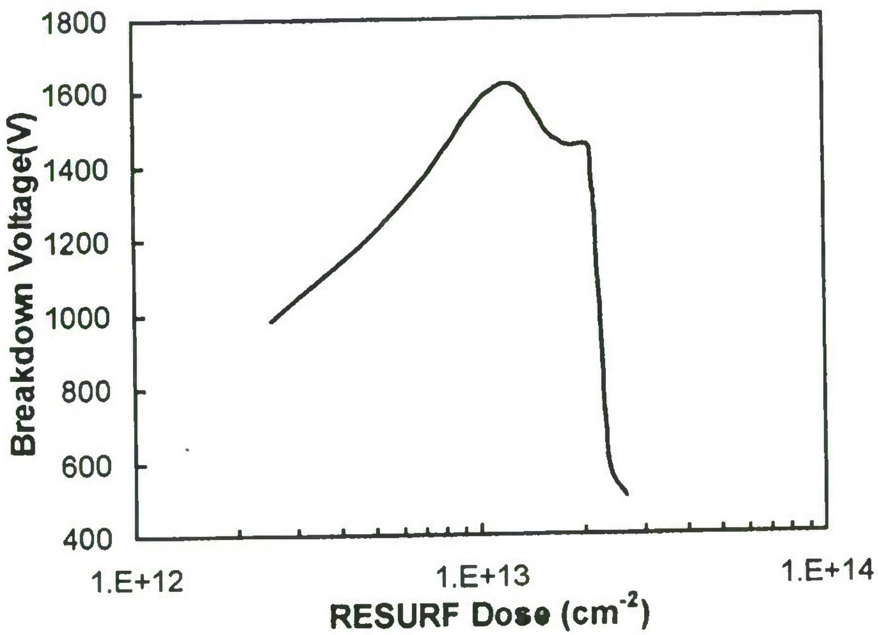


Rensselaer
T. P. Chow

Lateral RESURF MOSFET

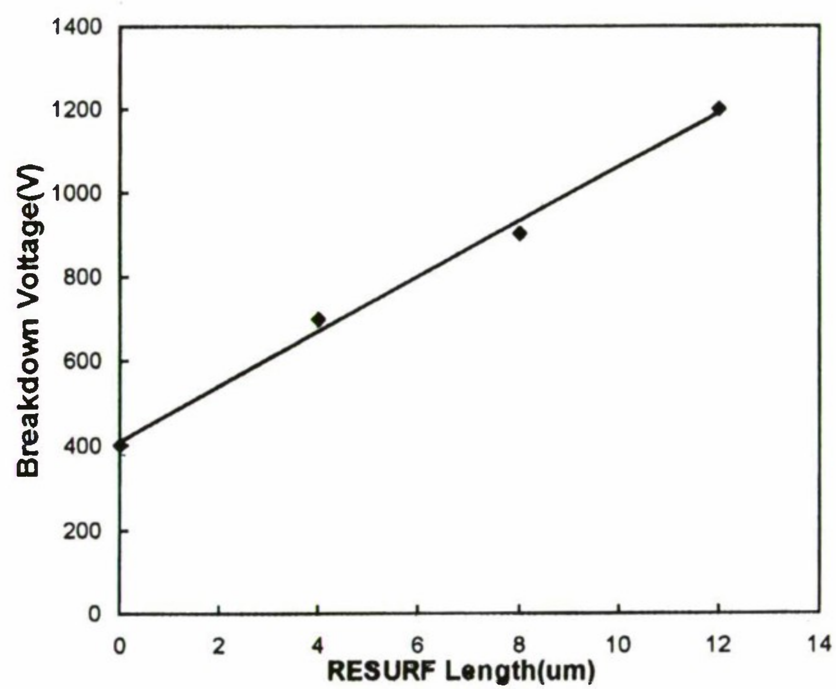


RESURF Dose vs. Breakdown Voltage

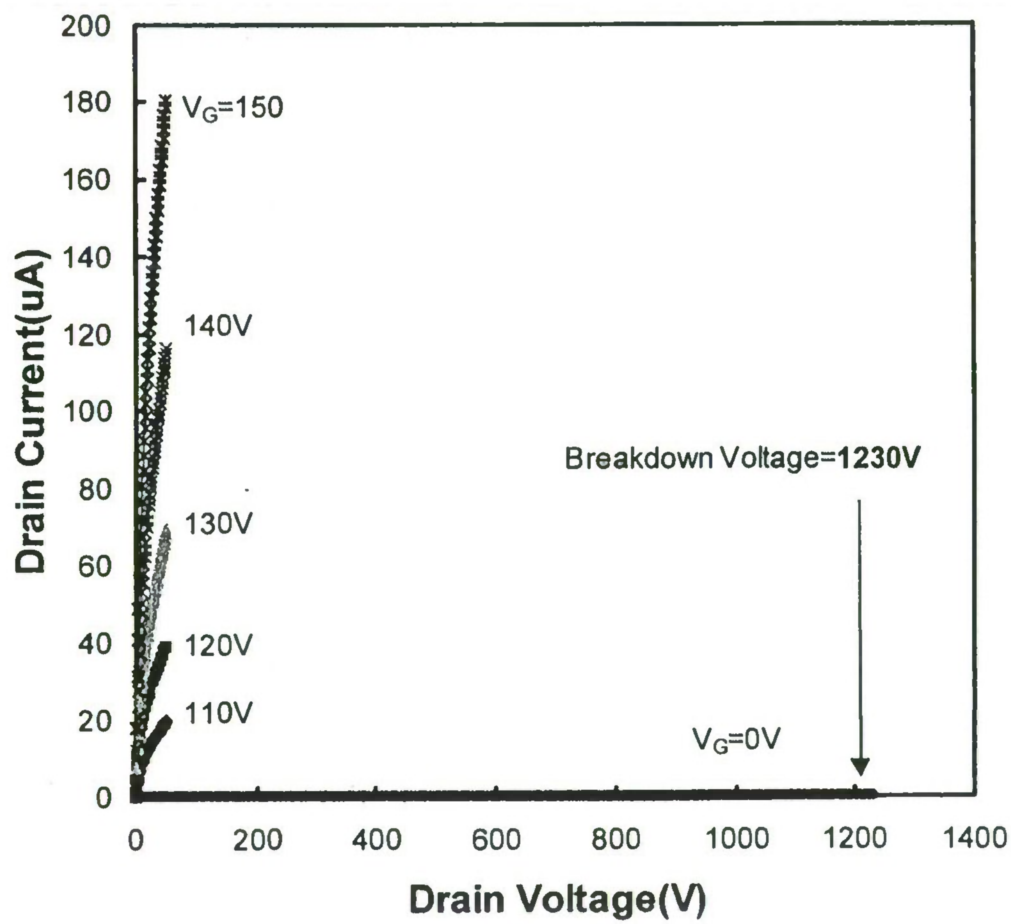


Simulated Data of RESURF Dose vs. Breakdown Voltage

Breakdown Voltage vs. Drift Length



I-V Characteristics



BV_{CEO} vs. $(1 - \alpha)$

- In silicon,

  BV_{CEO} (npn) $\sim (1-\alpha)^{1/4}$

  BV_{CEO} (pnp) $\sim (1-\alpha)^{1/6}$

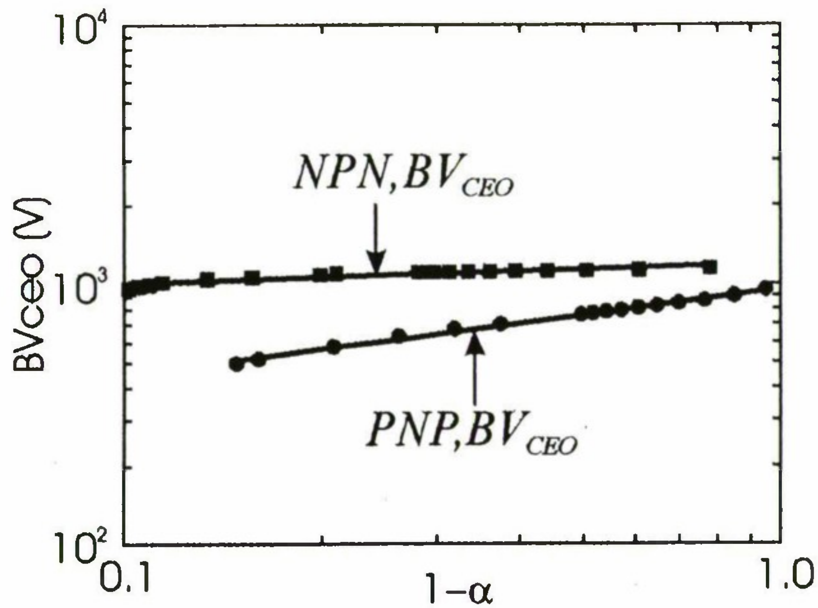
  because $\alpha_n > \alpha_p$. So, the SOA of pnp is larger than that of npn.

- In 4H-SiC,

  BV_{CEO} (npn) $\sim (1-\alpha)^{1/13}$

  BV_{CEO} (pnp) $\sim (1-\alpha)^{1/3}$

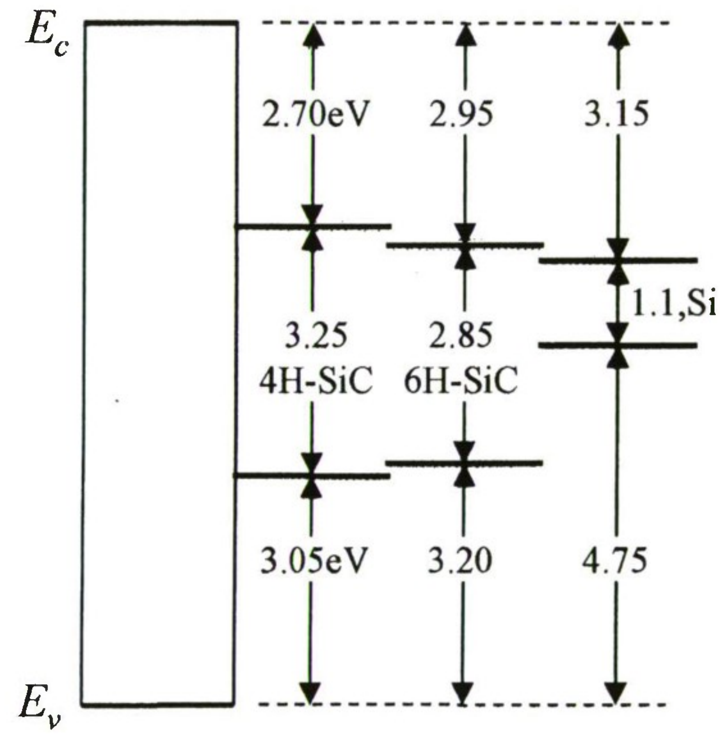
  because $\alpha_p > \alpha_n$. So, the SOA of npn is larger than that of pnp.



Recent Demonstrations of SiC High-Voltage Bipolar Transistors/Thyristors

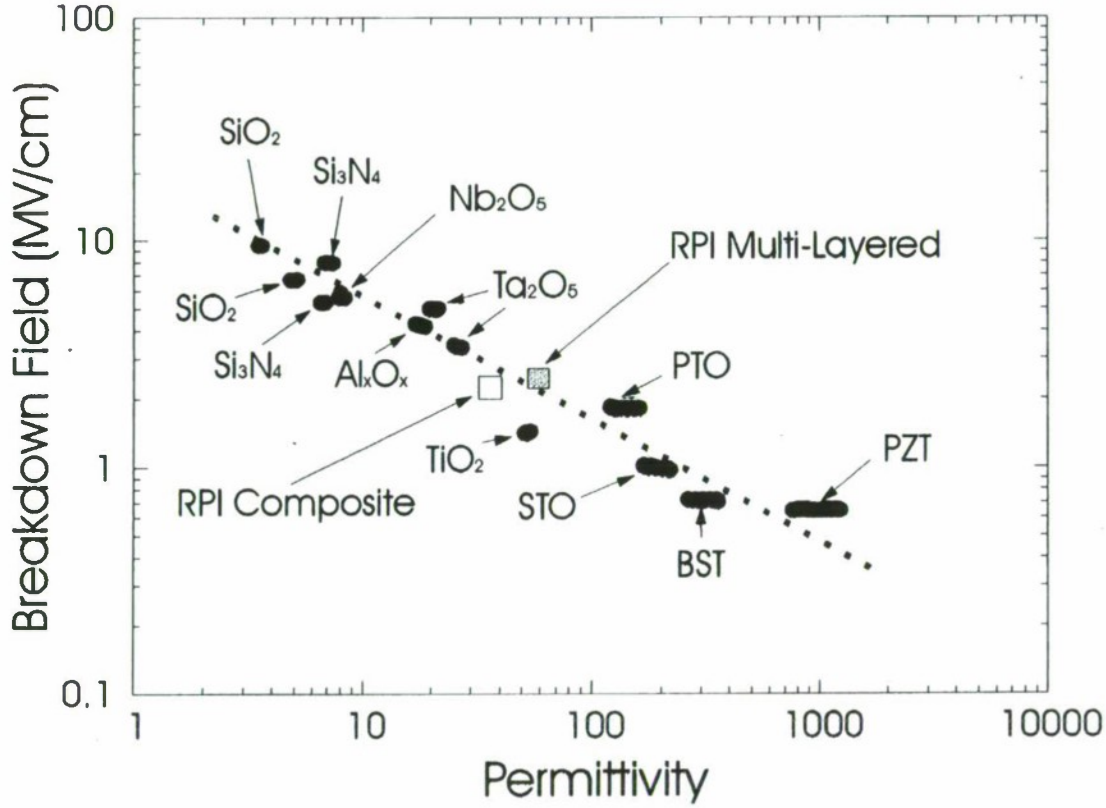
Device Type	Polytype	Power Ratings	Features	Researcher
BJT	6H-SiC	200V, 20mA	$\beta \sim 10$, 126m$\Omega \cdot cm^2$	Cree, 1993
IGBT	6H-SiC	200V, 1mA	Self-Aligned UMOS	RPI/GE, 1996
	4H-SiC	800V	Self-Aligned UMOS, p-channel	RPI, 1997
Thyristors	6H-SiC	100V, 20mA	Gate Triggered	Cree, 1993
	4H-SiC	900V, 2A	Gate Triggered, 0.82 m$\Omega \cdot cm^2$	Cree, 1996
	6H-SiC	100V, 1.8A	Gate Turn-Off (GTO) V_{F100}= 2.9V, J_{max}= 5200A/cm^2	ARL, 1995
	4H-SiC	600V, 4.2A	Gate Turn-Off (GTO), Involute Gate, (1600A/cm^2, V_F= 1.5V)	Northrop Grumman, 1997
	4H-SiC	600V	Implanted p+ Emitter	RPI, 1997
	4H-SiC	1100V	Gate Turn-Off (GTO)	GE/RPI, 1999

Energy Band Diagrams

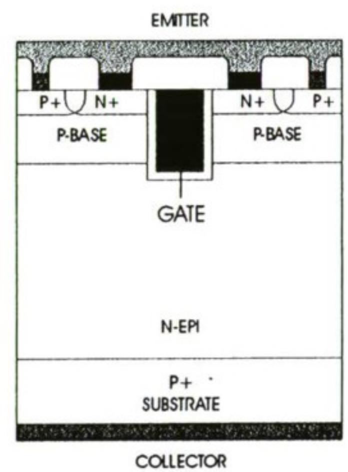


From: A.K. Agarwal, et.al., *"Temperature Dependence of Fowler-Nordheim Current in 6H- and 4H-SiC MOS Capacitors"*, EDL, Vol. 18, pp. 592-594, Dec. 1997.

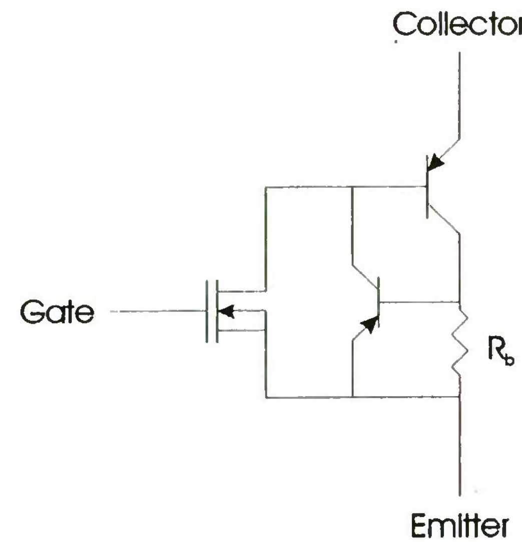
Dielectric Breakdown Field



Insulated-Gate Bipolar Transistor

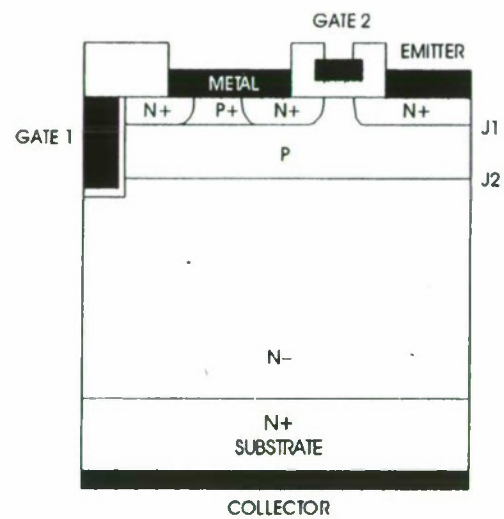


Insulated Gate Bipolar Transistors (IGBTs)

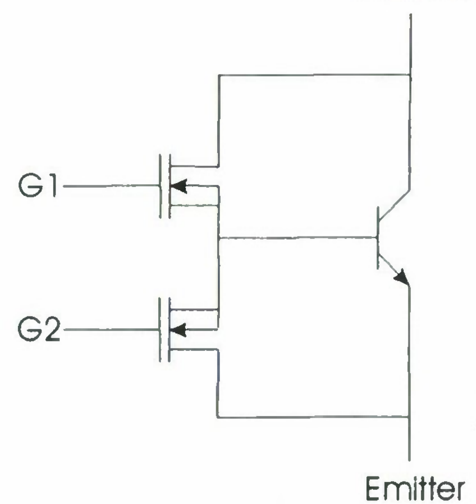


IGBT Equivalent Circuit

MOS-Gated Bipolar Transistor

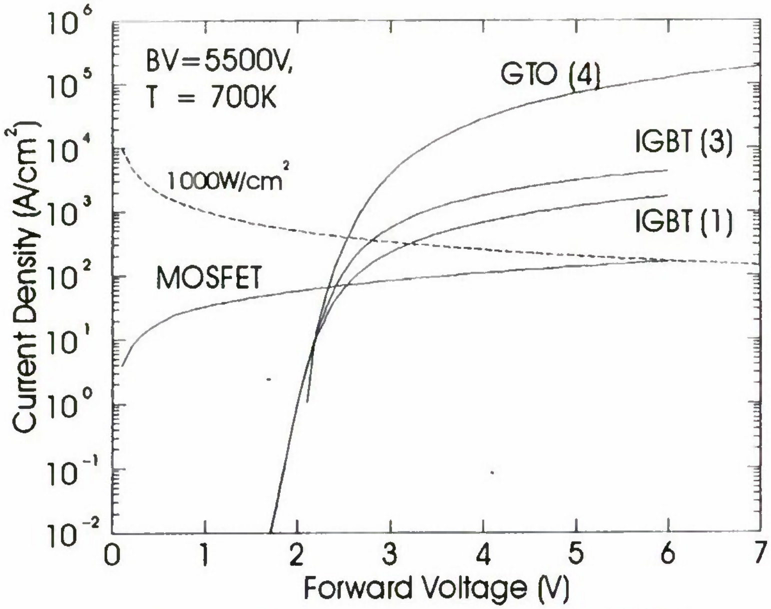


MOS Gated Transistors (MGTs)

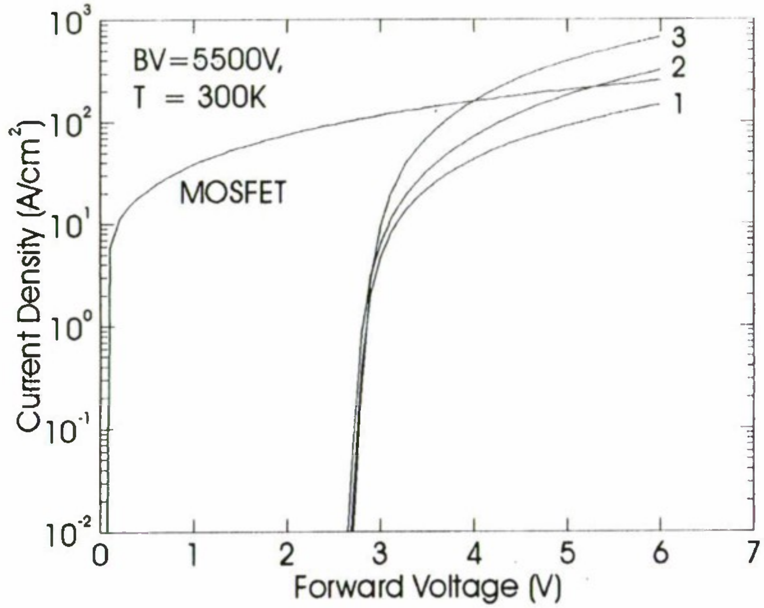


MGT's Equivalent Circuit

Forward I-V Characteristics



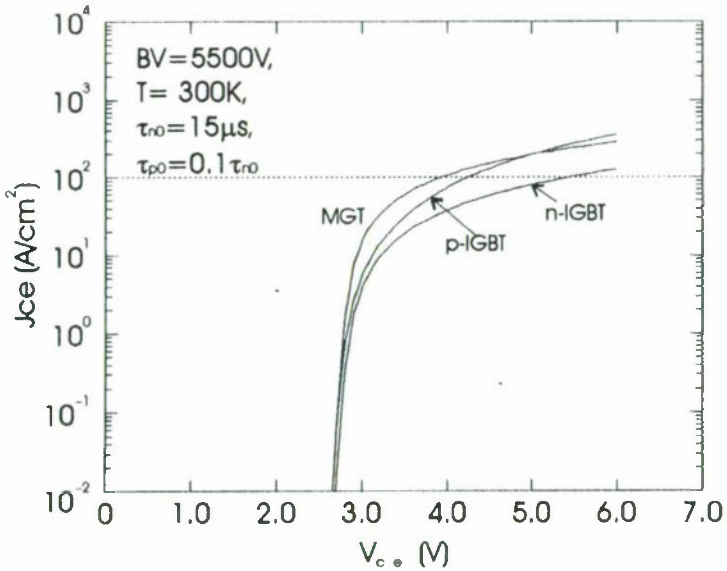
Forward I-V Characteristics of 5000V SiC GTO, IGBT, and MOSFET at 700K



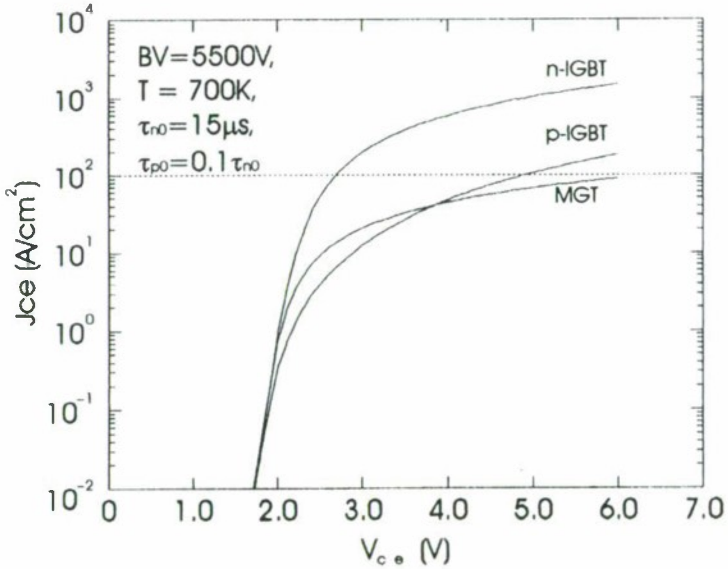
Forward I-V Characteristics of 5000V SiC IGBT, MOSFET at 300K

1: IGBT with commercially available substrate doping (τ_{p0}=1.5μs),
2: IGBT with 1-order-of magnitude improvement in substrate doping (τ_{p0}=1.5μs)
3: IGBT with 1-order-of magnitude improvement in substrate doping (τ_{p0}=5μs)
4: GTO with τ_{n0}=5.0μs, τ_{p0}=1.0μs
ALL WITH PUNCH THROUGH STRUCTURE

Forward I-V Characteristics

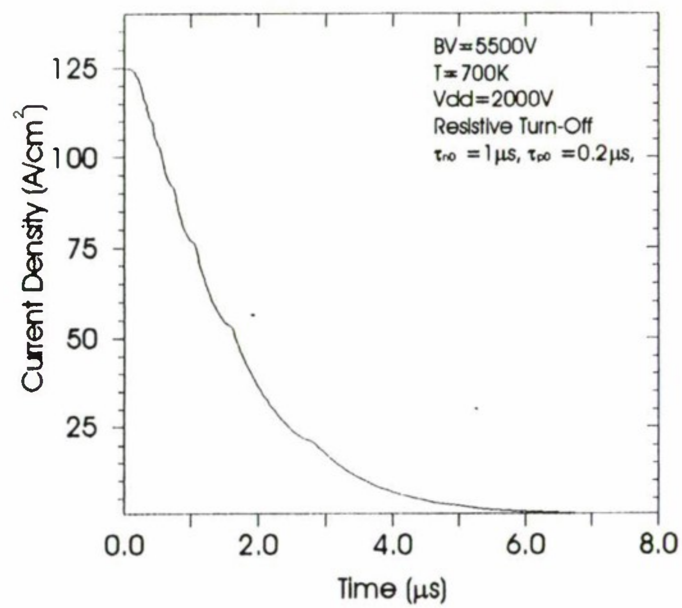


Forward I-V Characteristics of 5000V SiC n-IGBT, p-IGBT, and MGT at 300K

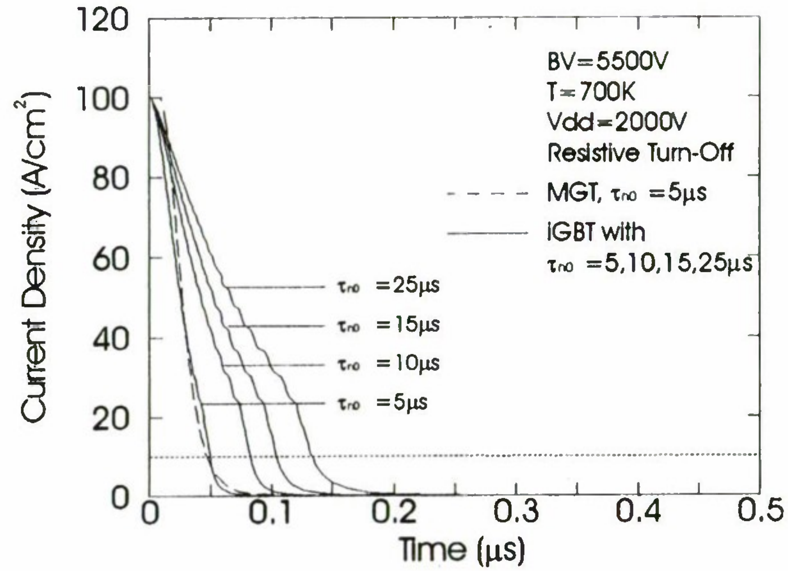


Forward I-V Characteristics of 5000V SiC n-IGBT, p-IGBT, and MGT at 700K

Turn-off Transients

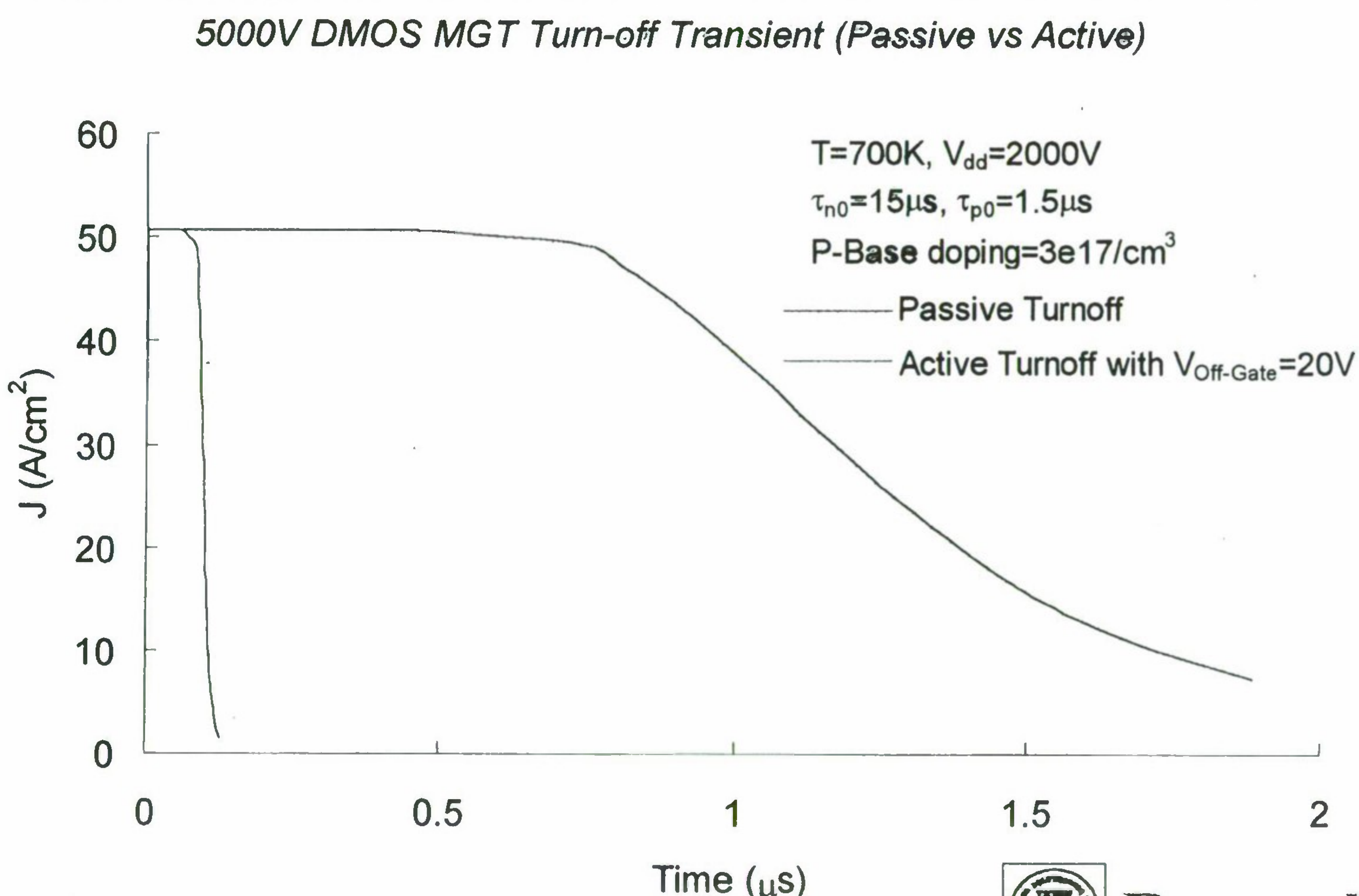


Turn-Off Transient of
a 5000V SiC GTO at 700K



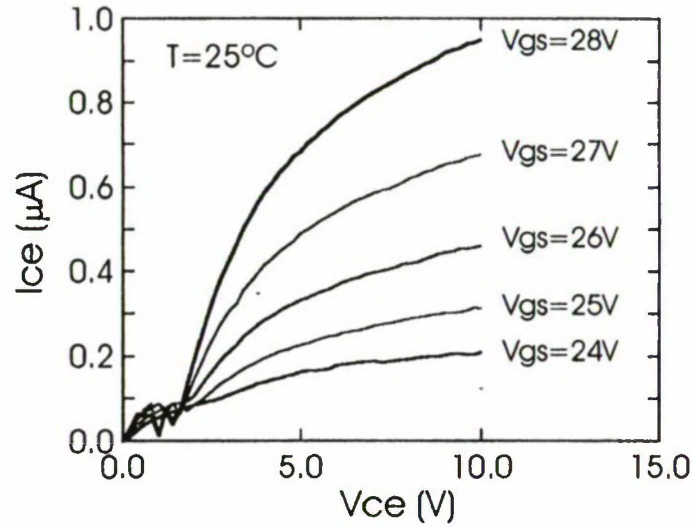
Turn-Off Transient of
5000V SiC IGBTs and MGT at 700K

MGT Turn-off Transients

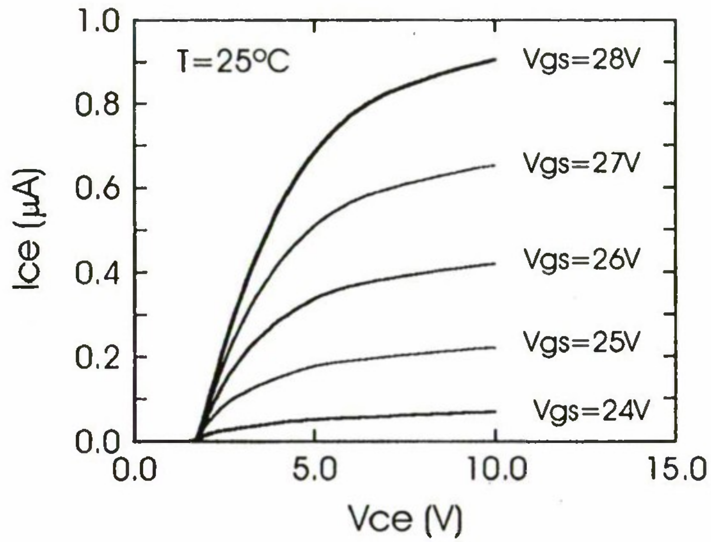


6H-SiC IGBT

Experimental and Simulated I-V Characteristics



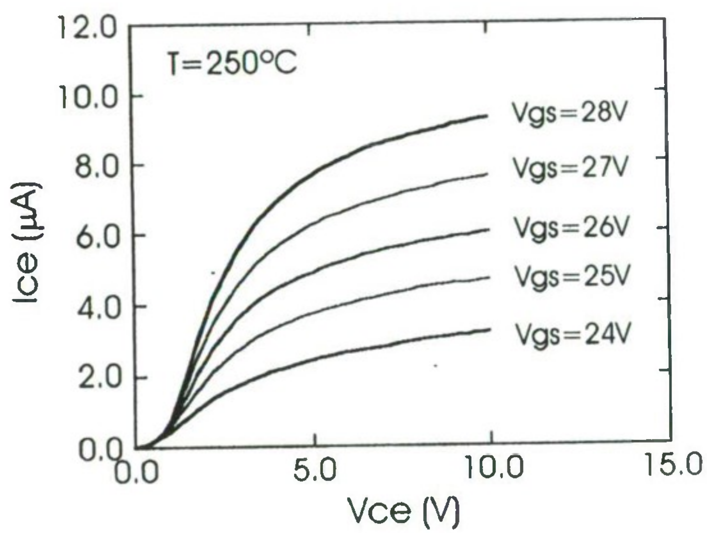
Measured current characteristics of 6H-SiC UMOS IGBT at room temperature



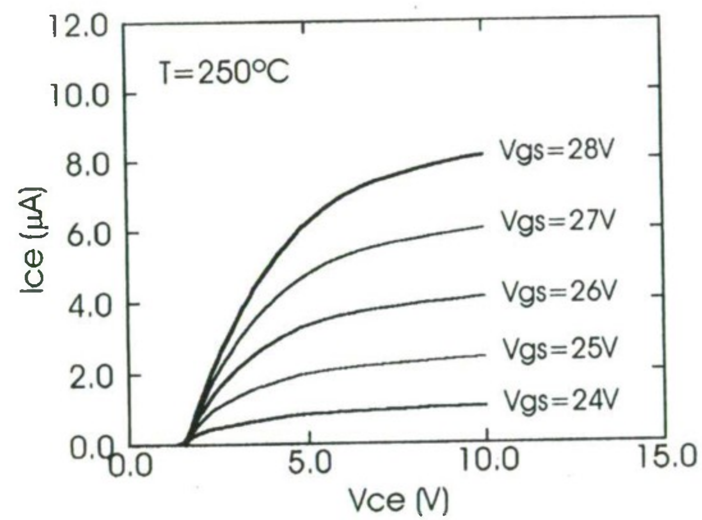
Calculated current characteristics of 6H-SiC UMOS IGBT at room temperature
(With : $\mu_{n(bulk)}=50\ cm^2/V\cdot s$, $\mu_{s(inv)}=6.25\times10^{-3} cm^2/V\cdot s$, $t_{ox}=1250Å$)

6H-SiC IGBT

Experimental and Simulated I-V Characteristics

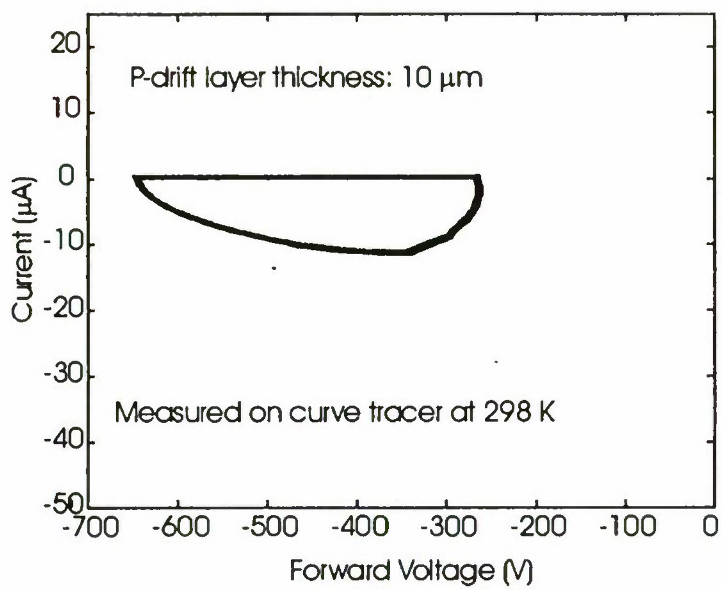


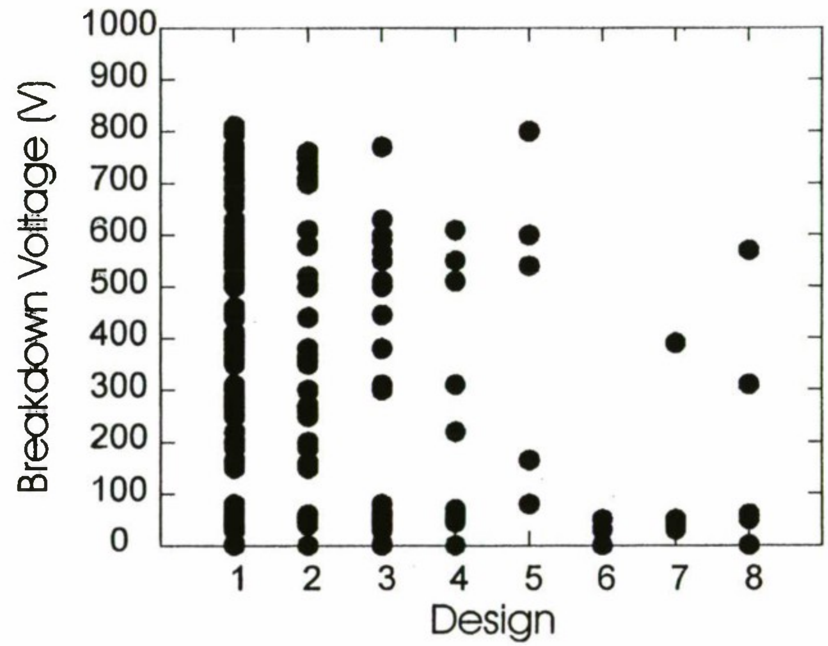
Measured current characteristics of 6H-SiC UMOS IGBT at 250°C



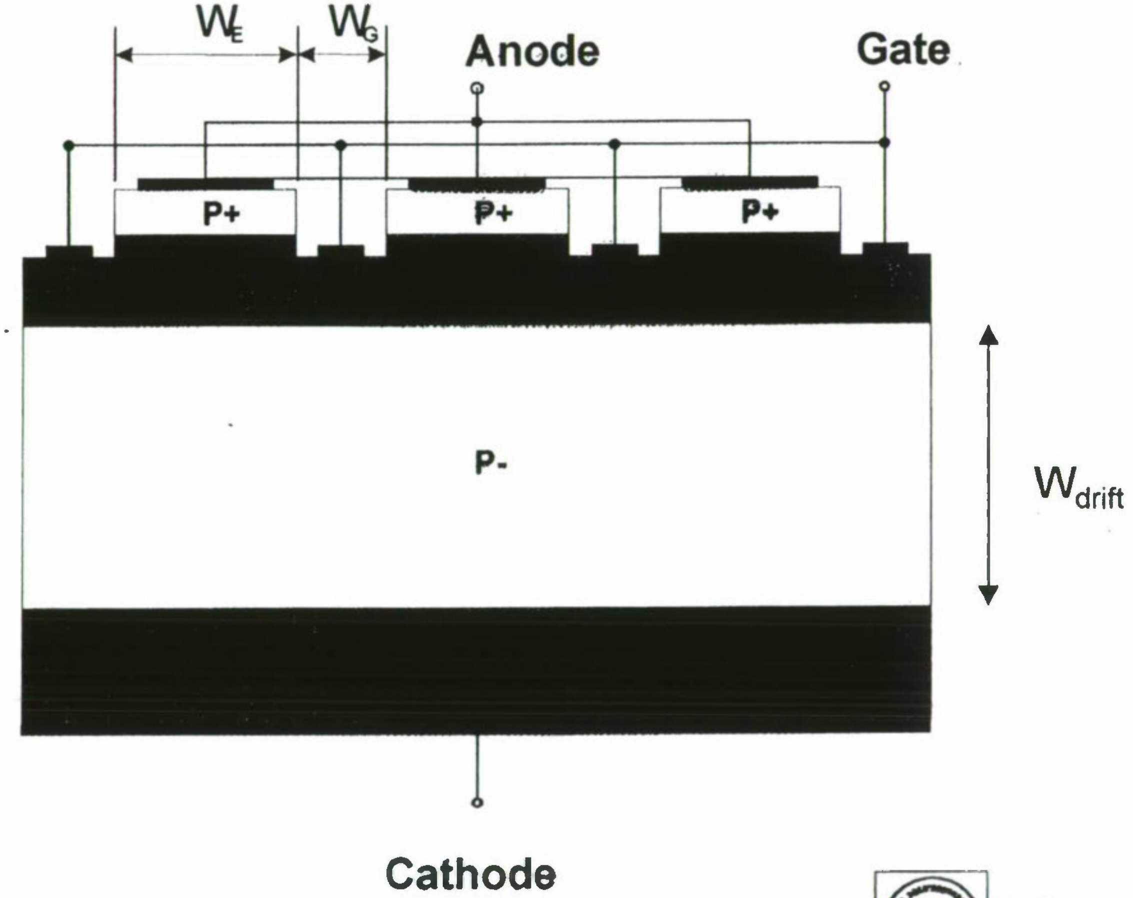
Calculated current characteristics of 6H-SiC UMOS IGBT at 250°C (With : $\mu_{n(bulk)}=50\ cm^2/V\cdot s$, $\mu_{s(inv)}=0.05cm^2/V\cdot s$, $t_{ox}=1250Å$)

4H-SiC p-channel UMOS IGBT

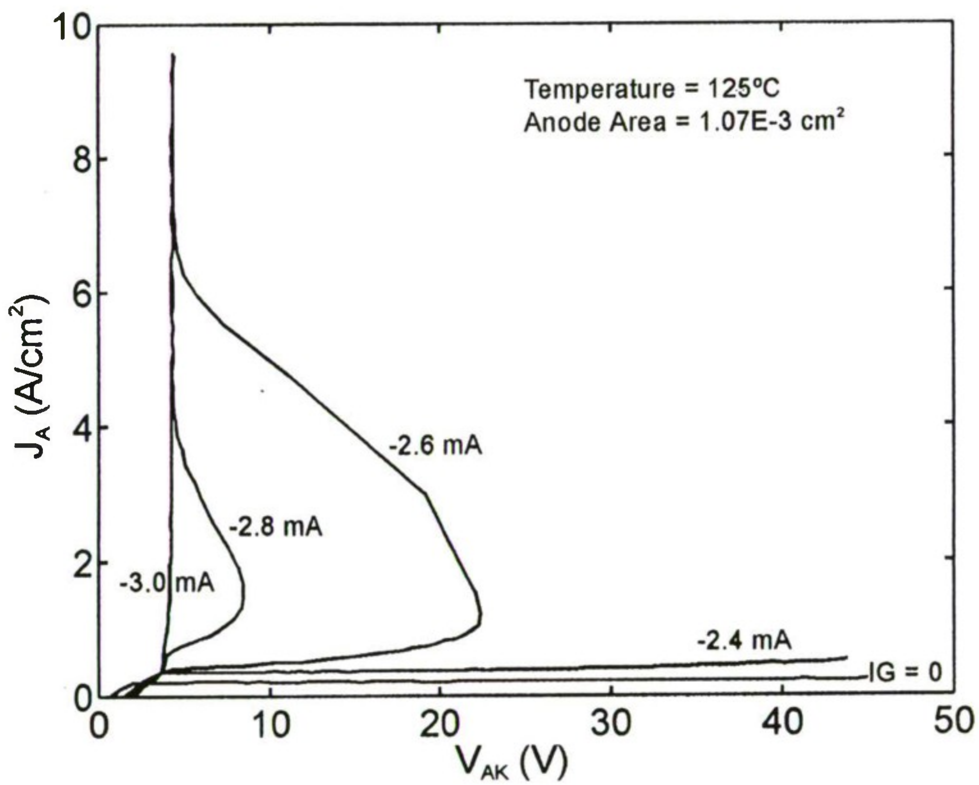




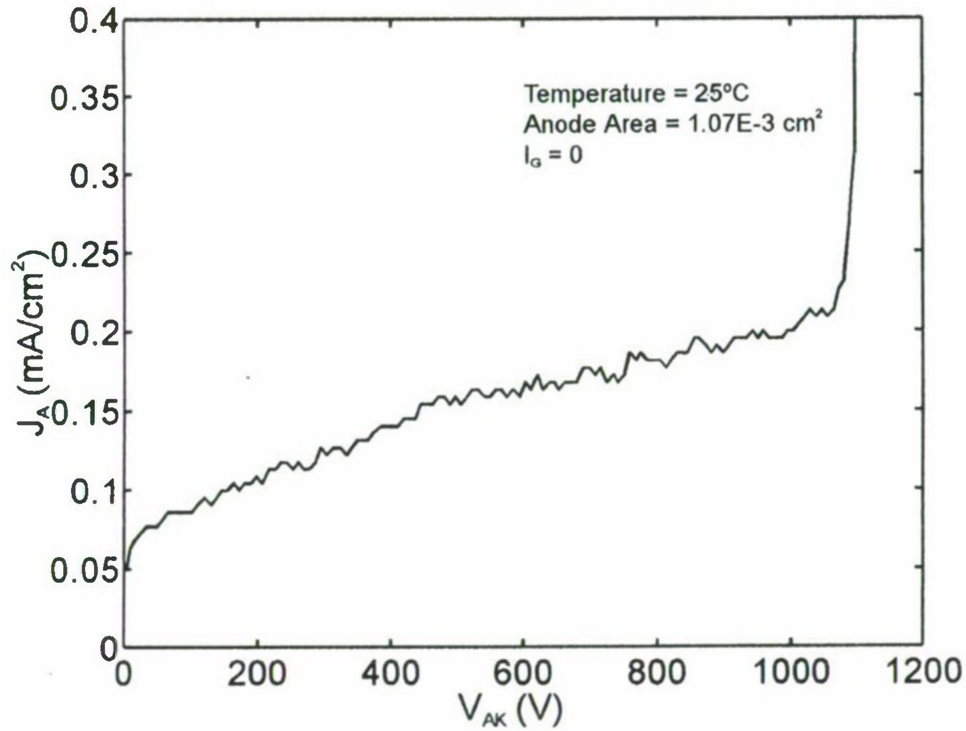
GTO Thyristor Cross-section



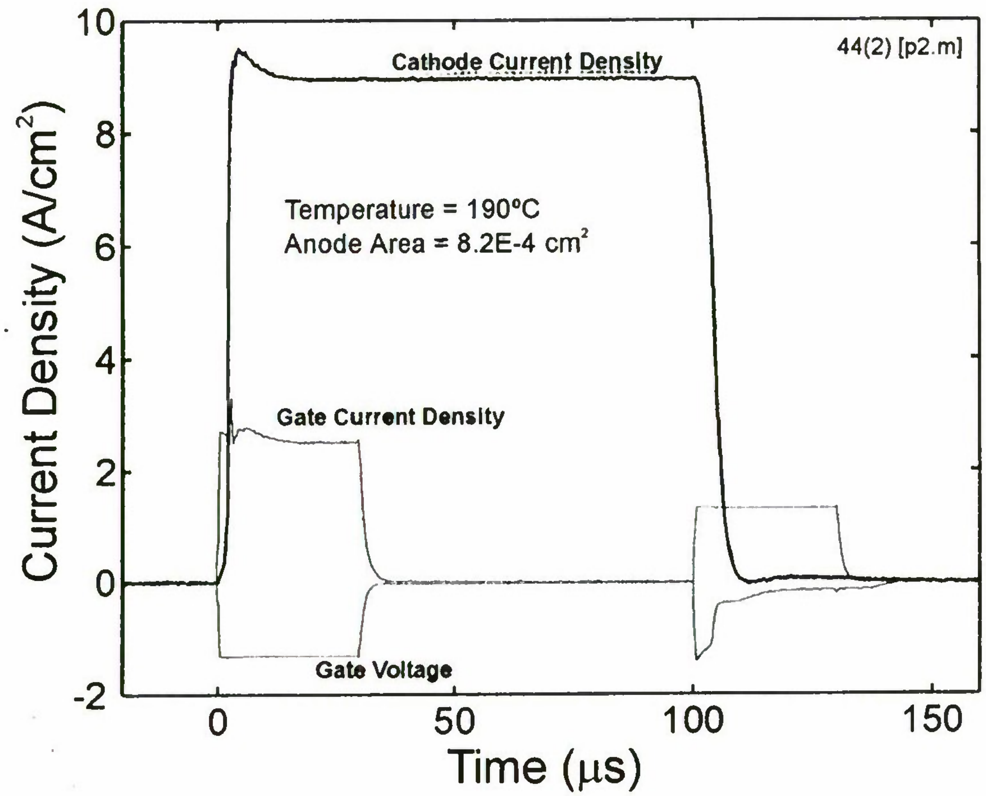
Forward On-State Characteristics of 4H-SiC GTO Thyristor



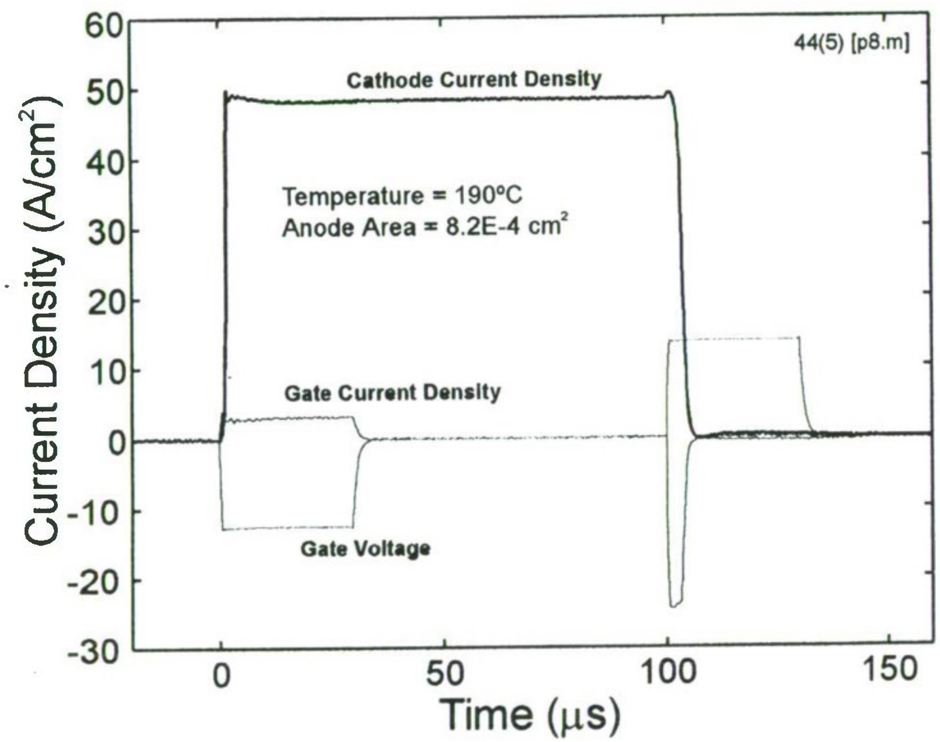
Forward Blocking Characteristics of 4H-SiC GTO Thyristor



GTO Thyristor
Switching Characteristics



GTO Thyristor
Switching Characteristics



MATERIAL AND PROCESS CHALLENGES

- **Identify and suppress the structural defects (e.g., screw dislocations) that cause excessive device leakage**
- **Maximize bulk minority carrier lifetime (> 1 μs) and surface recombination velocity (< 10 cm/s)**
- **Improve p-type doping control in epitaxial growth**
- **Improve the percentage activation and sheet resistance (< 1 KΩ/square) of p-type implanted layers**
- **Reduce specific Ohmic contact resistivity($< 10^{-5}$ Ω-cm^2) to p-type regions**
- **Enhance gate insulator reliability, particularly at elevated temperatures**

PEI Electronics Inc.

THE HYBRID ELECTRIC HMMWV DEVELOPMENT PROGRAM

A REVIEW

M98B034

PEI Electronics Inc.

THE PEI/TARDEC/DARPA HYBRID ELECTRIC HMMWV PROGRAM

- SINCE 1992, PEI ELECTRONICS, INC. HAS BEEN INVOLVED WITH TARDEC AND DARPA IN A COOPERATIVE RESEARCH AND DEVELOPMENT EFFORT TO EVALUATE TODAY'S HYBRID ELECTRIC VEHICLE TECHNOLOGY IN MILITARY APPLICATIONS
- IN 1993, PEI COMPLETED MODIFICATION OF AN ALL ELECTRIC HMMWV UTILIZING A COMMERCIAL DRIVE TRAIN FOR DEMONSTRATION PURPOSES.
- IN 1995, PEI INITIATED EFFORTS TO PRODUCE A HIGH PERFORMANCE HYBRID ELECTRIC HMMWV AS A PROOF OF PRINCIPLE VEHICLE FOR MILITARY APPLICATIONS AND FOR COMMERCIAL SALES.
- IN DECEMBER 1997, PEI/TARDEC/DARPA ROLLED OUT THE PROTOTYPE HMMWV AND DEMONSTRATED THE ACHIEVEMENT OF THE BASIC VEHICLE PERFORMANCE LEVELS.

PEI Electronics Inc.

PROGRAM OBJECTIVES

- DEVELOP A PROTOTYPE HMMWV WHICH MEETS OR EXCEEDS ALL PERFORMANCE CHARACTERISTICS OF A CONVENTIONALLY POWERED VEHICLE.
- DEMONSTRATE A SYSTEMS LEVEL APPROACH TO ACHIEVING PROGRAM GOALS.
- DEMONSTRATE A FULL FEATURED VEHICLE CONCEPT USING AN INTEGRATED DRIVE SYSTEM SUITABLE FOR BOTH MILITARY AND COMMERCIAL APPLICATIONS.
- SUCCESSFULLY INSERT THIS TECHNOLOGY INTO BOTH MILITARY AND COMMERCIAL MARKETS AT THE EARLIEST OPPORTUNITY.

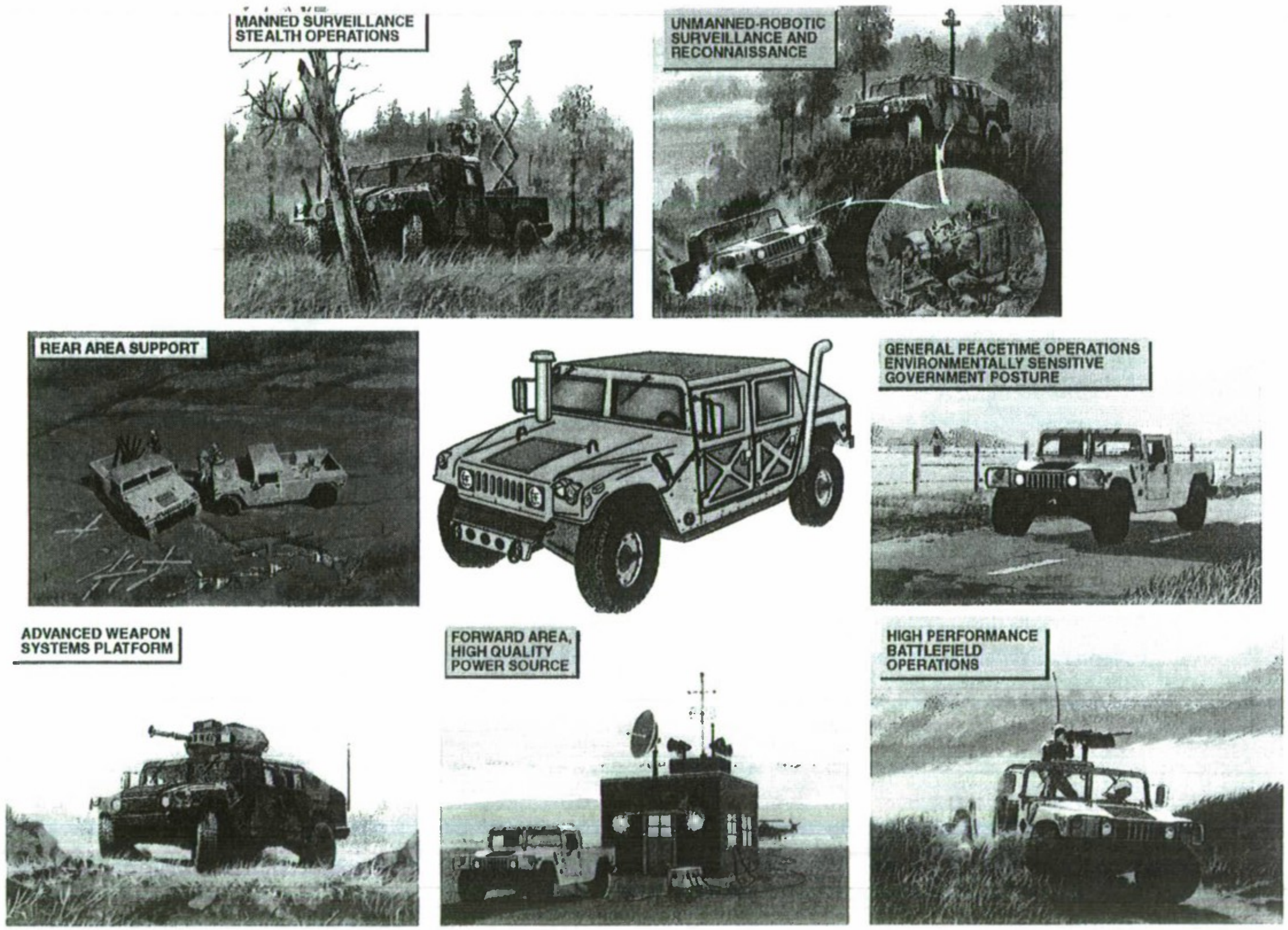
PEI Electronics Inc.

HYBRID ELECTRIC HMMWV PROGRAM
PHASE II PROTOTYPE

M98A038

PEI Electronics Inc.

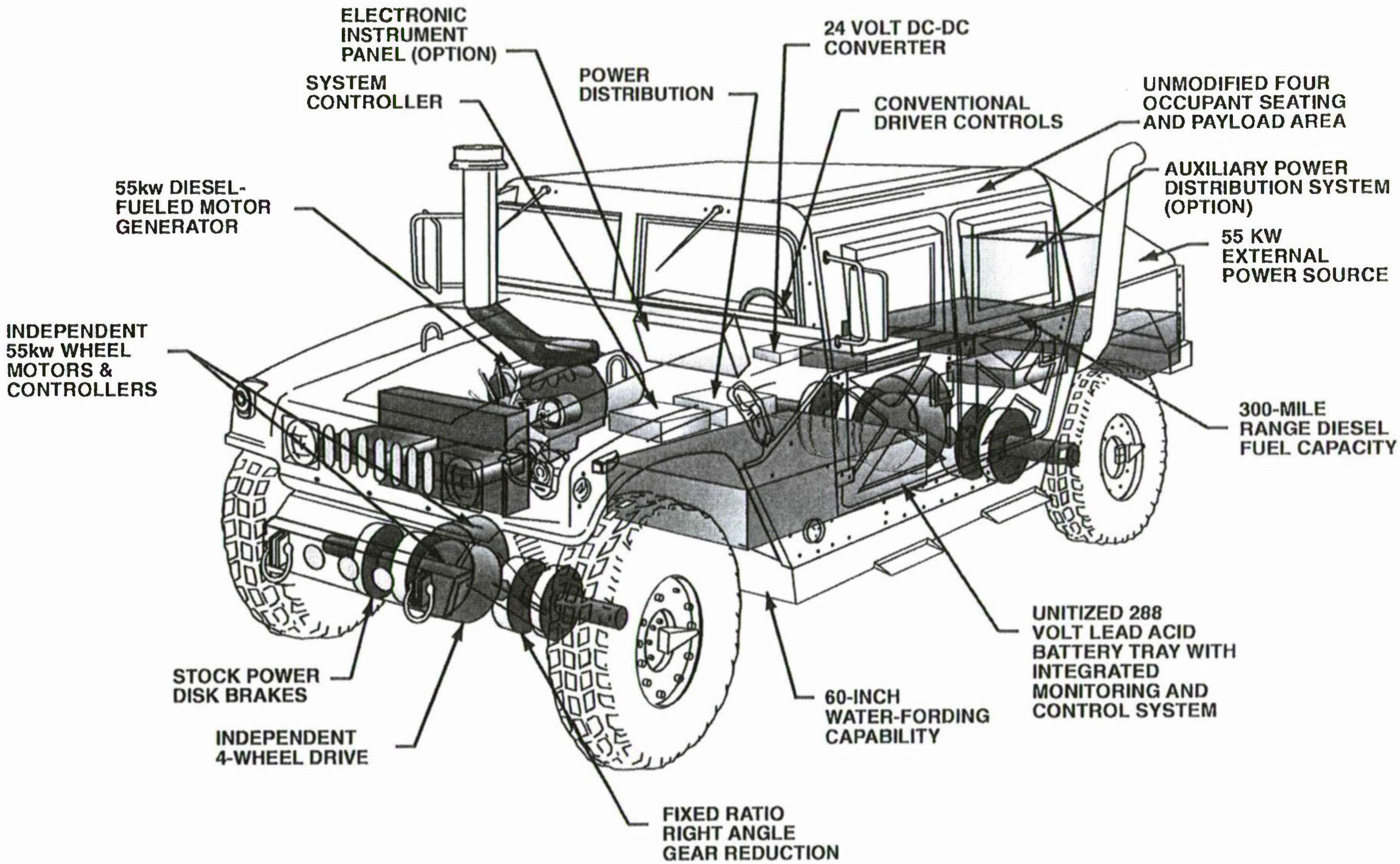
HYBRID ELECTRIC HMMWV MISSION PORTFOLIO



M97H000
(4-30-99)

PEI Electronics Inc.

THE HYBRID ELECTRIC HMMWV SYSTEM CONCEPT



M97K124 (3/9/99)

PEI Electronics Inc.

VEHICLE PERFORMANCE

M98B029C
(5-03-99)

PARAMETER	UNITS	TYPICAL STOCK	HYBRID HMMWV	
			LEAD ACID	NICKEL M-HYDRIDE
RANGE HYBRID ELECTRIC	MILES	275 N/A	350 20	350 20
TOP SPEED GRADE 0% 60%	MPH	70 6.8	85 17*	85 17*
ACCELERATION 0-50	SECONDS	14	7	7
PAYLOAD	POUNDS	3032-5150	+ 600**	- 0**
STORED ENERGY	KW-HRS	<1	24	24

* TRACTION LIMITED

** OVER (+) or UNDER (-) STOCK VEHICLE PAYLOAD

PEI Electronics Inc.

SYSTEM FEATURES

- ALL ELECTRIC OR HYBRID OPERATION
- HIGH POWERTRAIN PERFORMANCE
- RETAINS ALL CAPABILITIES OF A STANDARD HMMWV
- INCREASED TOP SPEED AND ACCELERATION
- LOW THERMAL SIGNATURE – ACTIVE COOLDOWN MODE
- LOW AUDIBLE NOISE - RUN SILENT MODE
- POWER STEERING AND BRAKES
- GRACEFUL DEGRADATION AND FAILOVER FOR INCREASED SURVIVABILITY
- PROVISIONS FOR OPERATION AS AN AUXILIARY POWER SOURCE
- EASILY ADAPTABLE TO ROBOTIC OPERATION
- INTERNAL AND EXTERNAL DIAGNOSTICS AND PROGNOSTICS

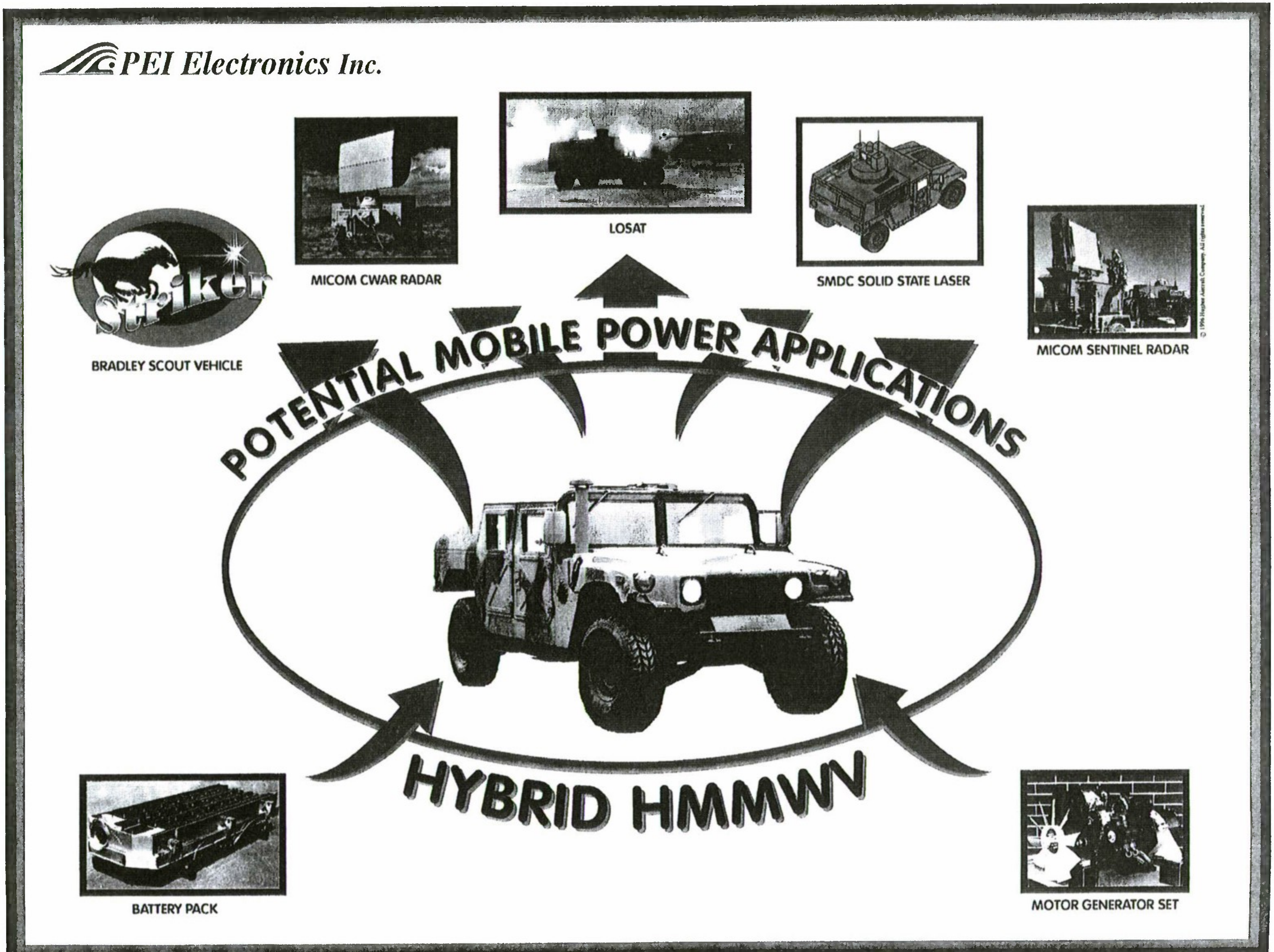
VG97F507

PEI Electronics Inc.

POWER TRAIN FEATURES

- DIESEL FUELED 55 KW MOTOR GENERATOR WITH PROVISIONS FOR RAPID COOLDOWN
- INTEGRATED, INTERCHANGEABLE BATTERY PACK WITH ADVANCED LEAD ACID BATTERIES PROVIDED STANDARD
- FULL BATTERY MANAGEMENT SYSTEM
- INDIVIDUAL 55 KW BRUSHLESS DC MOTOR DRIVE WITH INDEPENDENT MOTOR CONTROLS
- SYSTEMS CONTROL UNIT
- AUXILIARY 24 VOLT, 100 AMP SLI MAINTENANCE SUPPLY
- ON BOARD DIAGNOSTICS AND PROGNOSTICS
- OFF BOARD MAINTENANCE SYSTEM

VG97F508


PEI Electronics Inc.
Striker
BRADLEY SCOUT VEHICLE
MICOM CWAR RADAR
LOSAT
SMDC SOLID STATE LASER
MICOM SENTINEL RADAR
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POTENTIAL MOBILE POWER APPLICATIONS
HYBRID HMMWV
BATTERY PACK
MOTOR GENERATOR SET

M98J002

PEI Electronics Inc.

HMMWV DISASTER RELIEF


U.S. Army

"IN THE AFTERMATH OF HURRICANE ANDREW, ARMY RESERVE SOLDIERS ASSIST DEVASTATED COMMUNITIES DURING DISASTER RELIEF EFFORTS."

FROM ARMY MAGAZINE MARCH 1999

PEI Electronics Inc.

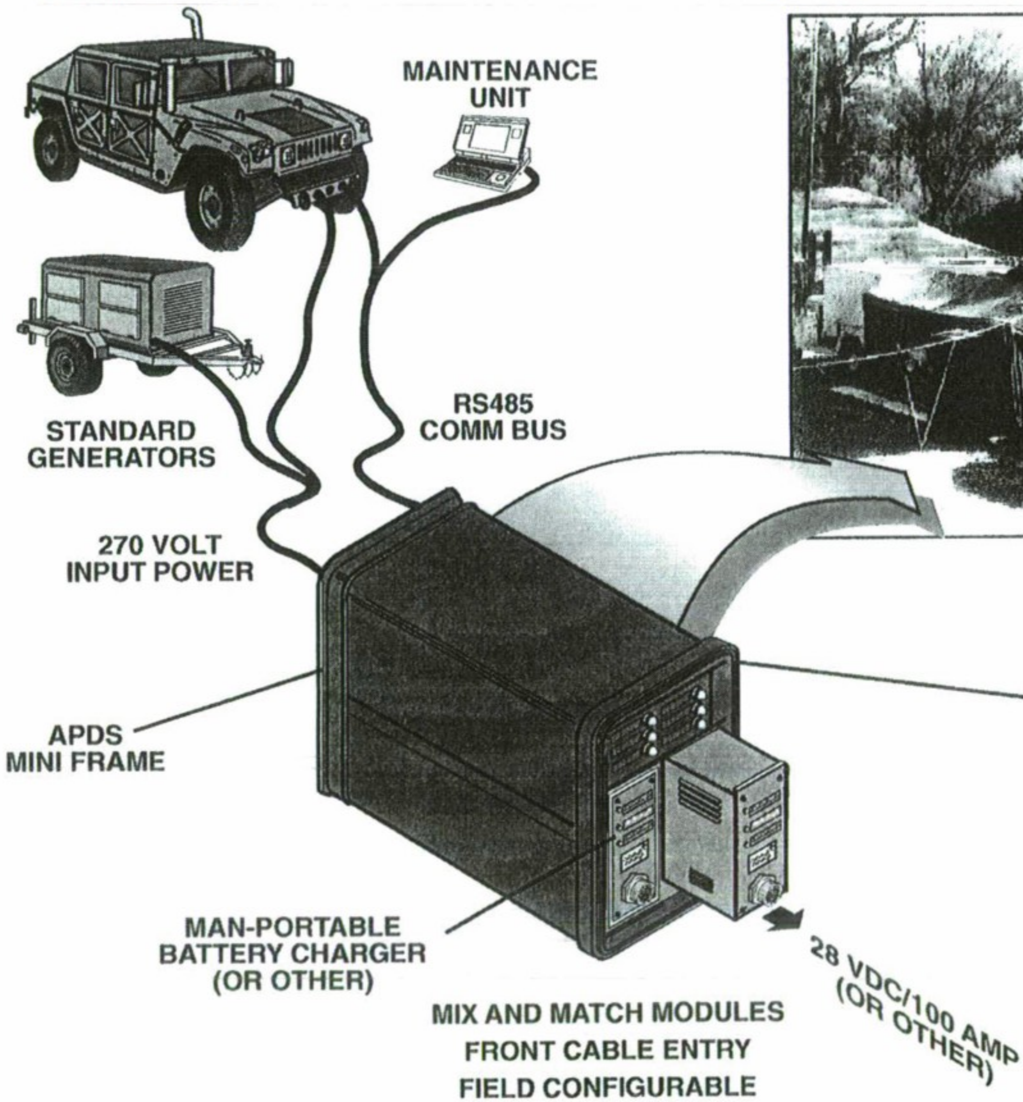
USE OF THE HYBRID HMMWV AS A MOBILE POWER SOURCE

- THE HYBRID HMMWV CARRIES ITS OWN GENERATION AND ENERGY STORAGE — NO EXTERNAL EQUIPMENT IS NEEDED.
- CONTINUOUS OPERATION FROM DIESEL FUEL RESERVE — BATTERY BACKUP FOR NON-INTERRUPTIBLE OPERATION.
- POWER IS AVAILABLE FOR USE ON OR OFF VEHICLE.
- AN INTEGRATED AUXILIARY ENERGY MANAGEMENT SYSTEM PROVIDES ANY VOLTAGE, CURRENT, FREQUENCY COMBINATION DESIRED INCLUDING:
  - 110 VOLTS AC UP TO 400 AMPS AT 50 TO 400 HZ
  - 12 OR 28 VOLTS DC UP TO 600 AMPS
- LOAD MANAGEMENT INCLUDES LOAD CONTROL, LOAD SHEDDING, AND DIAGNOSTIC MONITORING.

VG97F516

PEI Electronics Inc.

APPLICATION SPECIFIC POWER DISTRIBUTION SYSTEMS

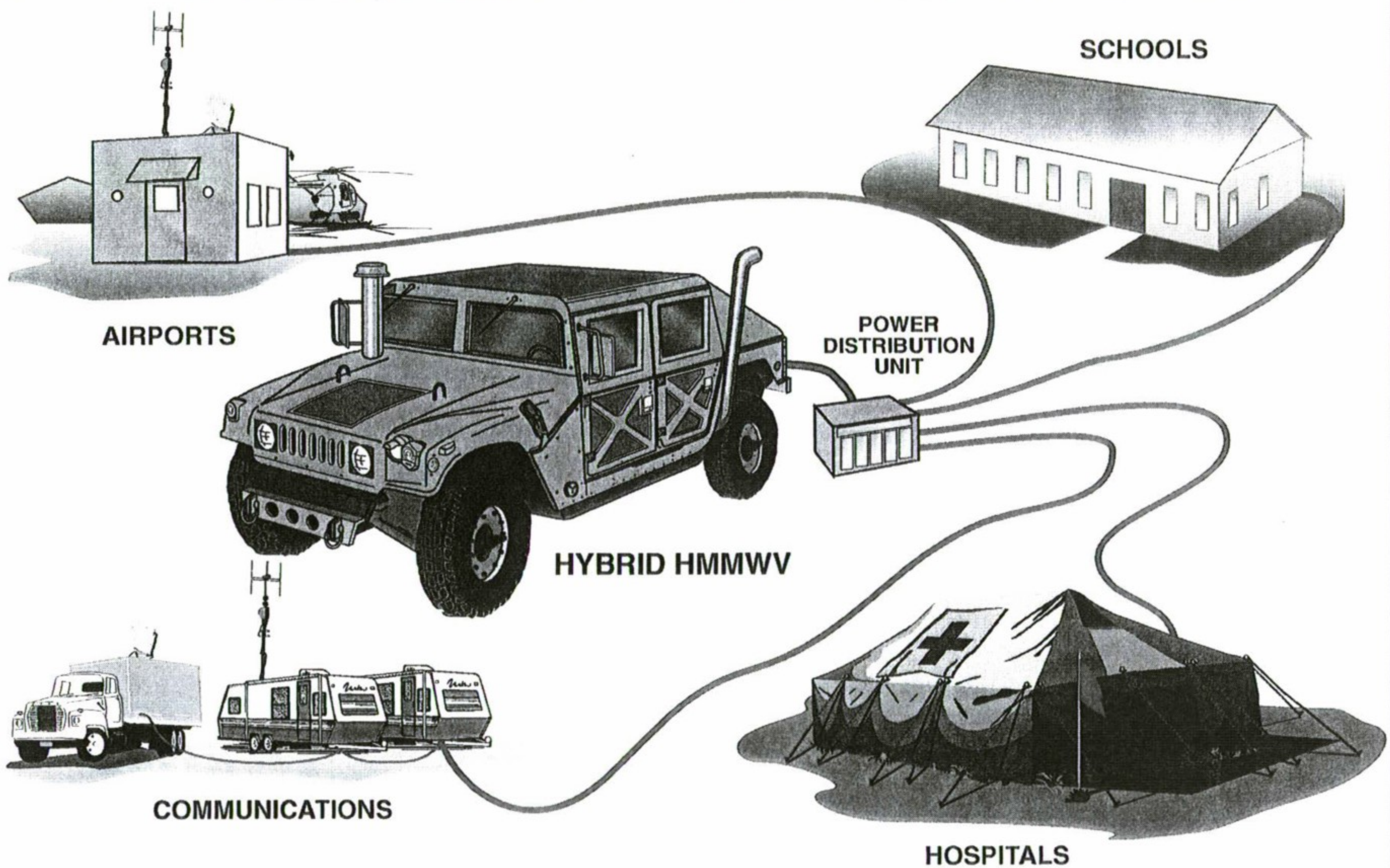


SUPPORT OF MOBILE TACTICAL OPERATIONS CENTER

M98J029A
(3-4-99)

PEI Electronics Inc.

HYBRID ELECTRIC HMMWV POWER MANAGEMENT AND DISTRIBUTION



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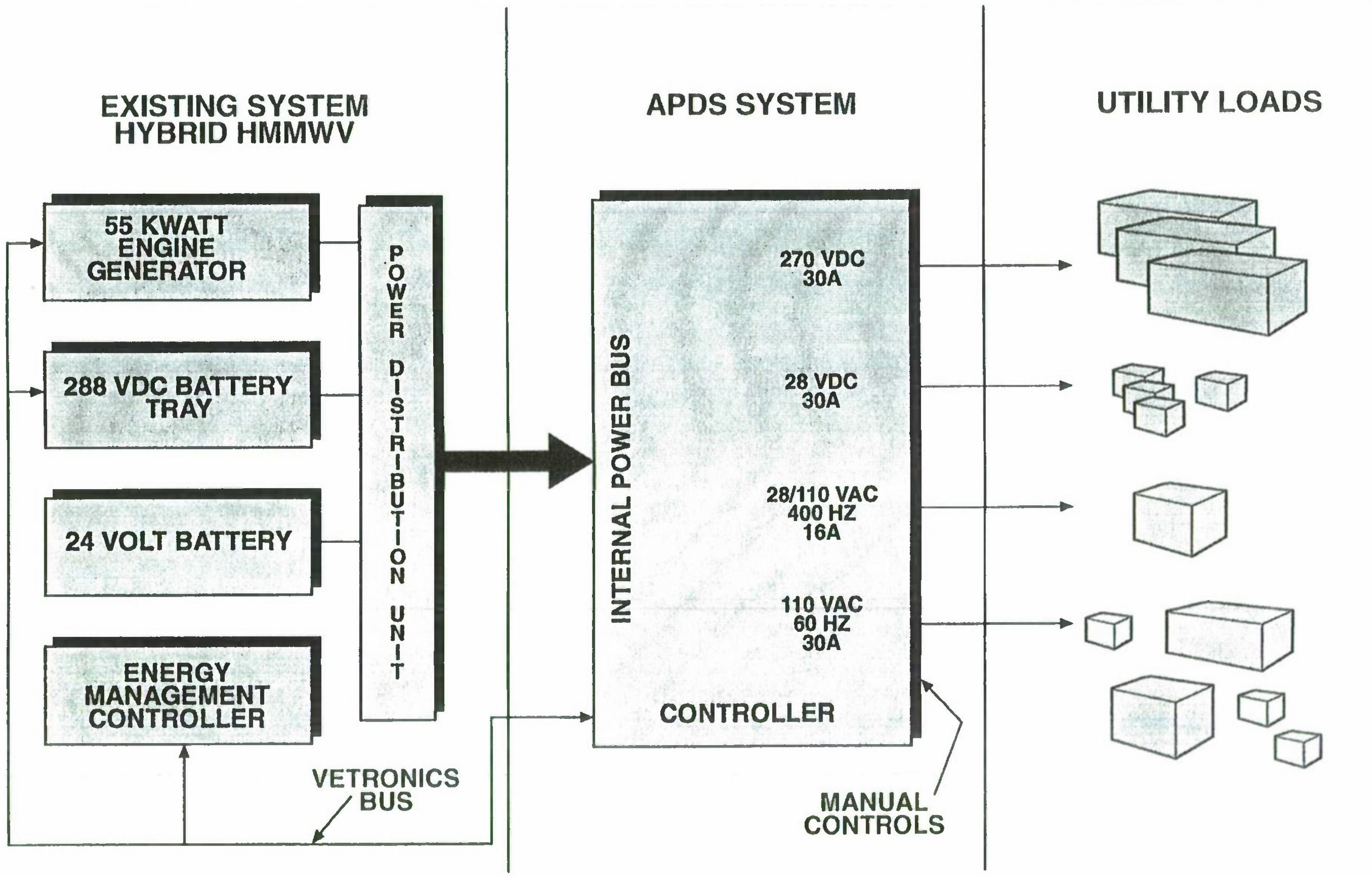
PEI Electronics Inc.

A MULTIPURPOSE UTILITY POWER DISTRIBUTION SYSTEM FOR THE H-HMMWV

M98J028
(10/19 /98)



PEI Electronics Inc.

THE HYBRID TROUBLE-TRUCK PROGRAM

REQUIREMENT:

- DESIGN, FABRICATE, TEST AND EVALUATE A HYBRID UTILITY TROUBLE TRUCK FOR POTENTIAL FLEET USE BY SOUTHERN COMPANY

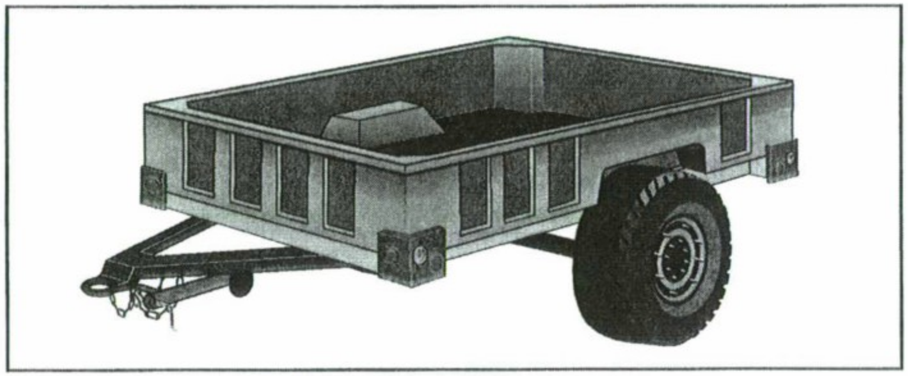
FEATURES:

- SIMILAR TO AVS BUS POWERTRAIN
- UTILIZES PEI ENGINE GENERATOR
- DRAMATICALLY IMPROVES OPERATIONAL FUEL ECONOMY
- ELECTRIC OVER HYDRAULIC POWERED BOOM SYSTEM
- AUXILIARY POWER AVAILABLE FOR SERVICE LIGHTS AND POWERED TOOLS/EQUIPMENT

PEI Electronics Inc.

POWERED TRAILER

REQUIREMENT:
PROVIDE AN ELECTRIC DRIVE SYSTEM FOR A HIGH MOBILITY MILITARY TRAILER THAT INCREASES MOBILITY AND MISSION EFFECTIVENESS OF THE VEHICLE/TRAILER PAIR.

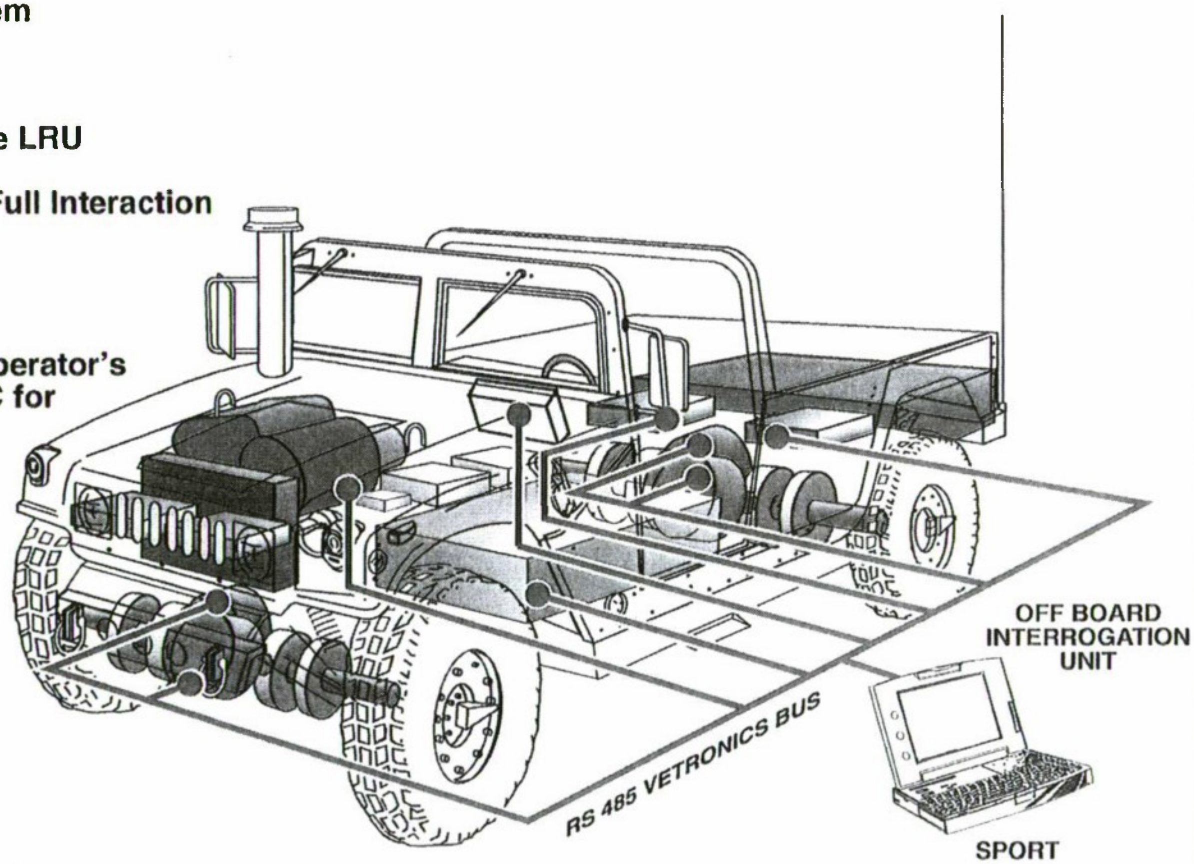


FEATURES:
- SIGNIFICANTLY INCREASED PAYLOAD AND MOBILITY
- USES SAME ELECTRIC DRIVE AS HYBRID HMMWV
- PROVIDES SAME PERFORMANCE CAPABILITY AS THE HYBRID HMMWV
- MAINTAINS CONSTANT DRAW BAR FORCE
- PROVIDES ELECTRIC DRIVE AND REGENERATIVE BRAKING
- PROVIDES LIMITED SELF-POWERED OPERATION FOR REPOSITIONING WITHOUT VEHICLE
- ADAPTABLE FOR USE WITH CONVENTIONALLY POWERED VEHICLES AT LOWER PERFORMANCE LEVELS
- SCALEABLE TO LARGE SEMITRAILERS AND EQUIPMENT HAULERS

PEI Electronics Inc.

HYBRID POWERTRAIN DIAGNOSTICS

- Fully Embedded Diagnostics and Prognostics
- Real-Time Evaluation of Vehicle Condition
- Compensation of Vehicle Operation Based on Status
- Prioritized Error Reporting System
- Sequence of Events Recording
- Capable of Isolating Faults to the LRU
- Interface with Off-Board PC for Full Interaction with Maintenance Personnel
- Compatible with Sport
- Optional On-Board Electronic Operator's Instrument Panel Acts as the PC for a Fully Embedded System with Interactive IETM and Maintenance Features

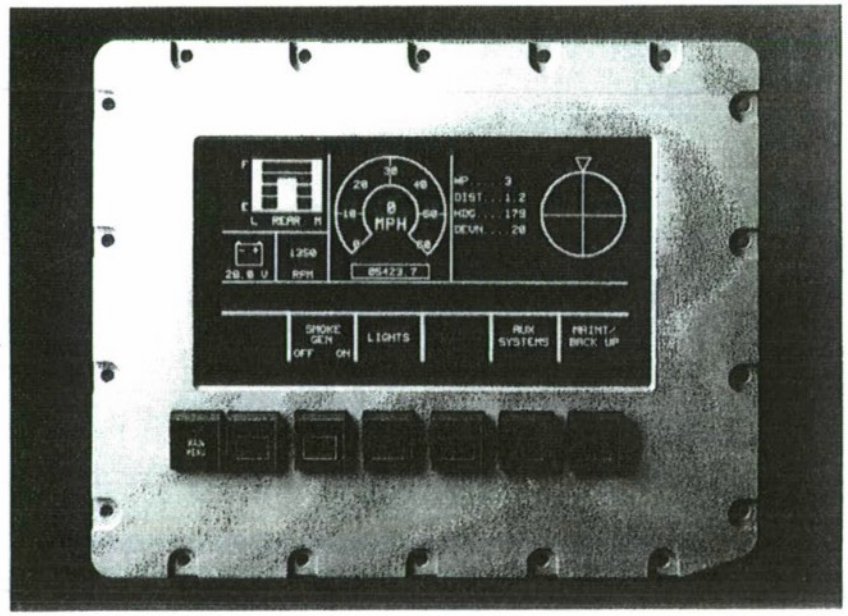


M99C013
(3-4-99)

PEI Electronics Inc.

OPERATOR'S INSTRUMENT PANEL

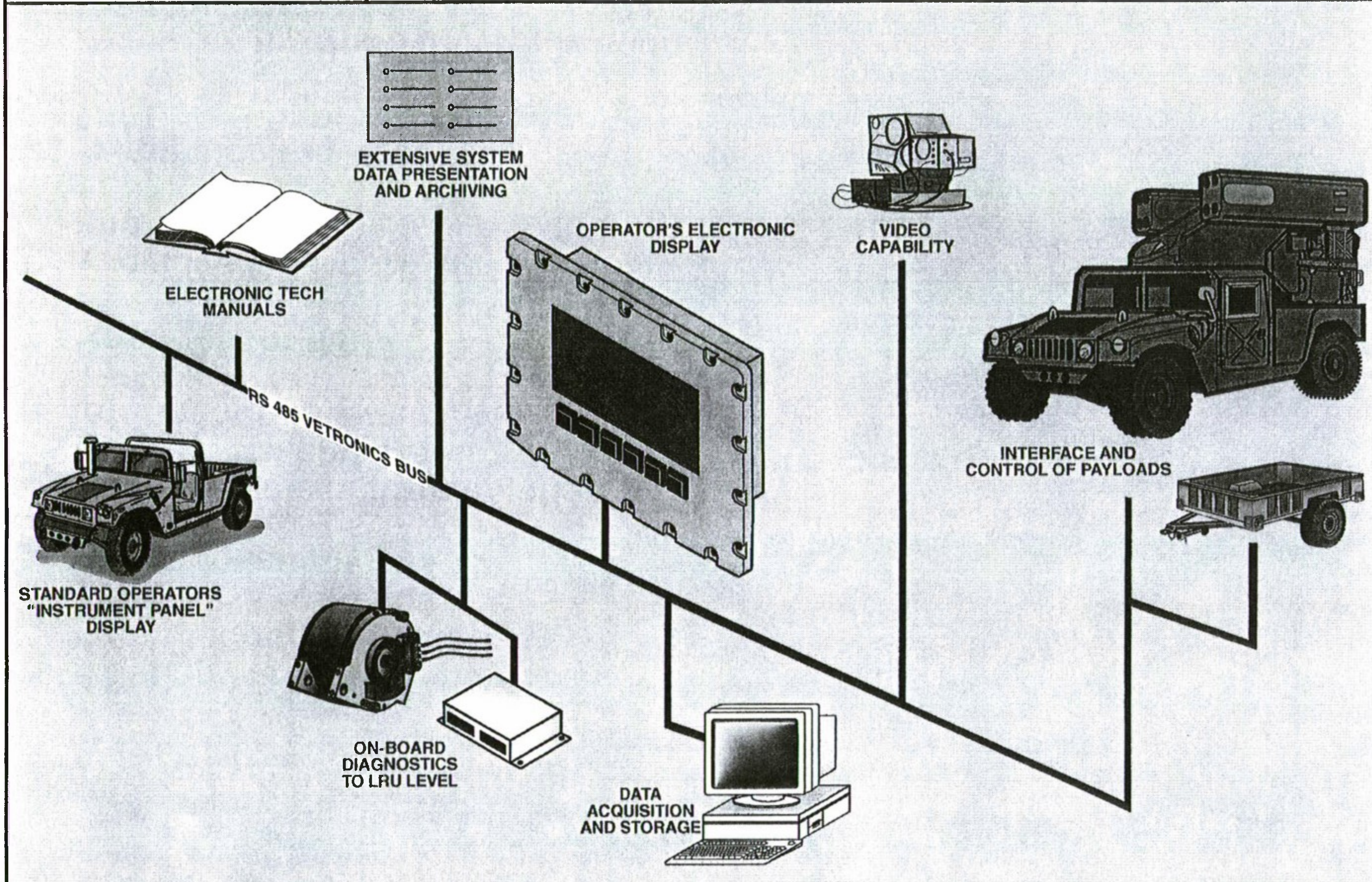
- Existing H-HMMWV Interfaces With Electronic Displays VIA RS485 Vetronics Communication Bus
- Basic Vehicle Instrumentation, Diagnostics and Status Information is Available
- Provides for IETM
- Provides On-Board Maintenance and Test
- Eliminates the Need for Off-Board Sport Equipment
- Available for Use With Application Specific Payloads
- Video Interface for External Sensors



M99C012
(3-4-99)

PEI Electronics Inc.

ELECTRONIC OPERATOR'S INSTRUMENT PANEL



M99C014
(3-4-99)

PEI Electronics Inc.

PROGRAM STATUS

- ROLL-OUT WAS IN DECEMBER, 1997.
- PERFORMANCE AND RELIABILITY HAS BEEN VERY GOOD.
- VEHICLE WEIGHT IS HIGH DUE TO THE USE OF OTS EQUIPMENT.
- GENERATOR OUTPUT IS THERMALLY CONSTRAINED.
- THE BATTERY WAS REPLACED AFTER 2 YEARS OF SERVICE.
- THE VEHICLE HAS BEEN INSTRUMENTED FOR ABERDEEN TESTING.
- HEAVY DEMONSTRATION/EVALUATION SCHEDULES HAVE DELAYED START OF TESTS.
- WORK HAS BEGUN ON A NEW TEST BED VEHICLE TO HELP EXPEDITE DEVELOPMENTAL ACTIVITIES.

PEI Electronics Inc.

ABERDEEN TESTING

- A/B COMPARISON TESTING OF HYBRID AND CONVENTIONAL POWERTRAIN TECHNOLOGIES.
- EMPHASIS ON:
  - FUEL ECONOMY
  - OVERALL POWERTRAIN PERFORMANCE
  - MOBILITY
  - EFFECTS ON MISSION SUCCESS.
- ON-ROAD/OFF-ROAD TESTING
- THREE-MONTH DURATION.

ABERDEEN PROVING GROUND
MARYLAND

M99E006
(5-3-99)

Hybrid Electric Drive Bradley

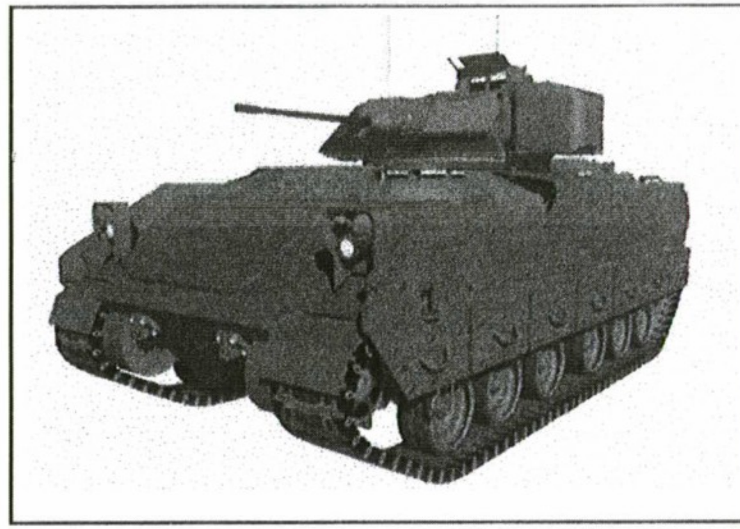
Alan M Loss
United Defense
5 May 99

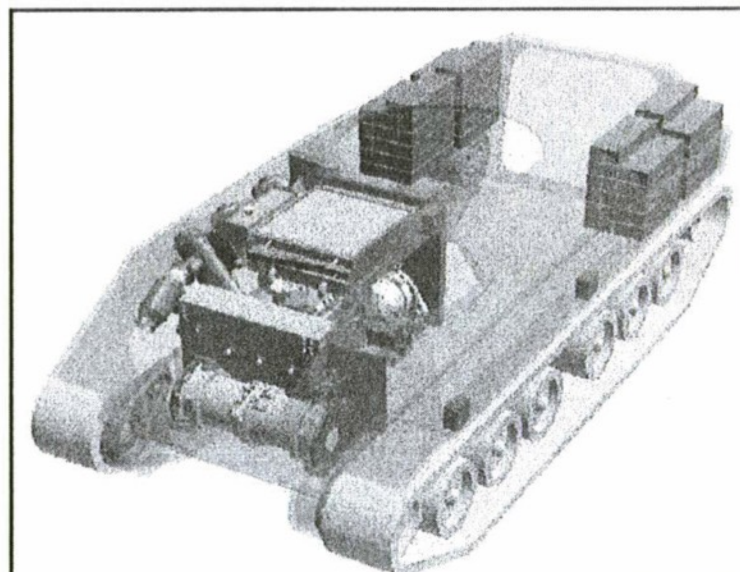
Hybrid Electric Drive BFV Demonstrator

United Defense

DARPA TARDEC

- **Objectives**
  - Demonstrate automotive and operational advantages of hybrid electric drive for tracked combat vehicles
  - Develop high power density electric drive components for heavy-duty applications
  - Technical Challenges:
    - High power density drive motors and power conversion hardware
    - Component and system cooling
    - Vehicle control system providing multiple modes of operation and maximum efficiency
- **Approach**
  - Develop a hybrid electric propulsion system that includes equipment for power generation, energy storage, sprocket torque production, and power management and distribution
  - Fabricate and install demonstrator hardware in a BFV-A0 personnel carrier
  - Support vehicle testing and demonstration





Hybrid Electric Drive Offers Many Benefits for Tracked Combat Vehicles

United Defense

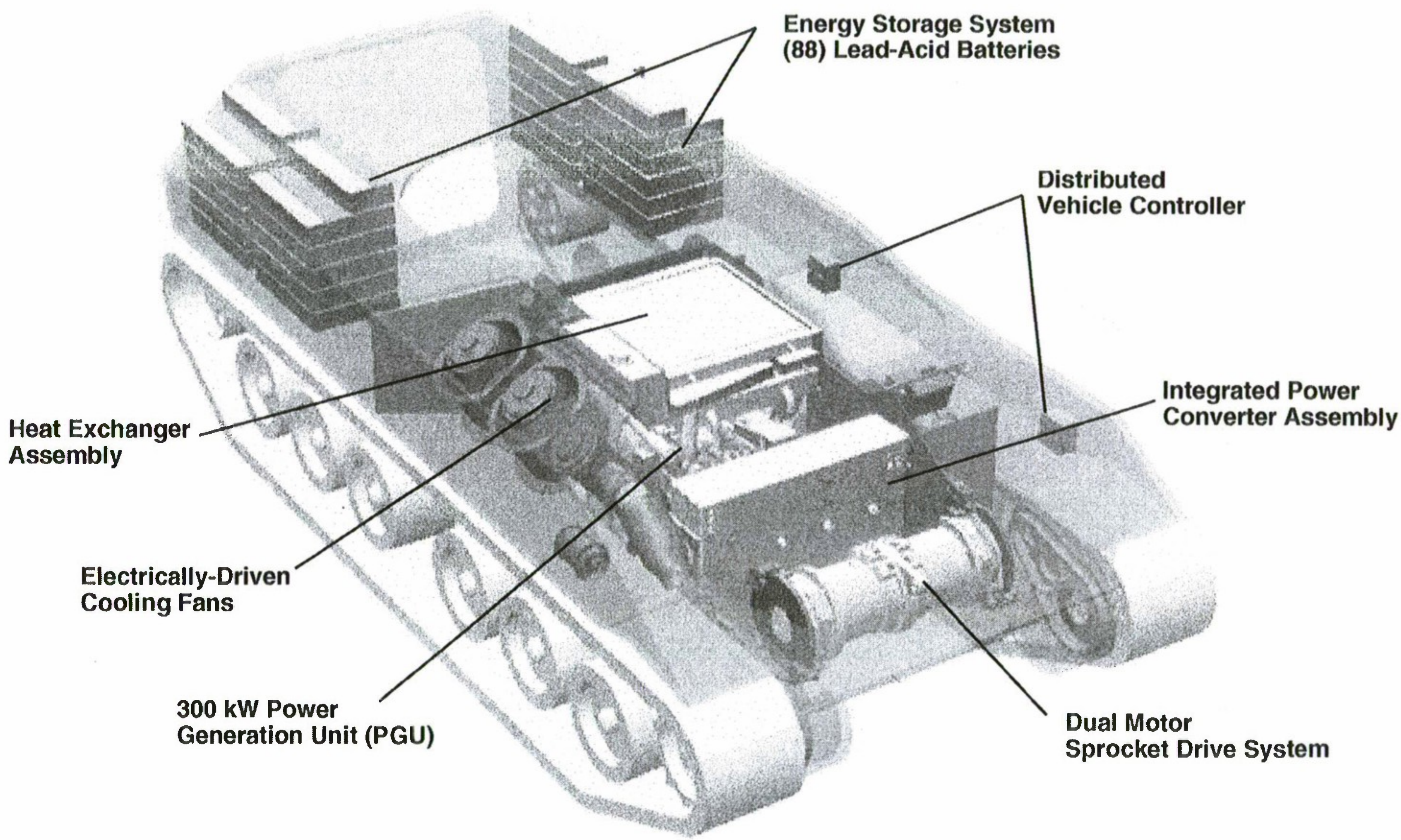
DARPA TARDEC

- **Greater Agility**
  - Higher acceleration and performance due to high power output of energy storage system and full power availability at all speeds
  - Increases maneuverability due to immediate torque to the tracks
- **Improved Range**
  - Improved fuel economy by operating a smaller engine under optimum conditions
  - Braking energy recovered by battery packs
  - Lower fuel consumption allows greater range or less on-board fuel storage.
- **Stealth Operation**
  - Battery energy storage system allows silent mobility and extended silent watch
  - Lower thermal, visual and acoustic signature with smaller engine and traction system
- **Other Benefits**
  - Electrical capabilities enables advanced technologies such as EM Armor, ETC guns or laser systems
  - Flexibility in placement of modular components readily adapts to variations in vehicle configurations
  - As new/better components and controls are developed they can be easily incorporated as product improvements

Hybrid Electric BFV Demonstrator - Drive System Arrangement

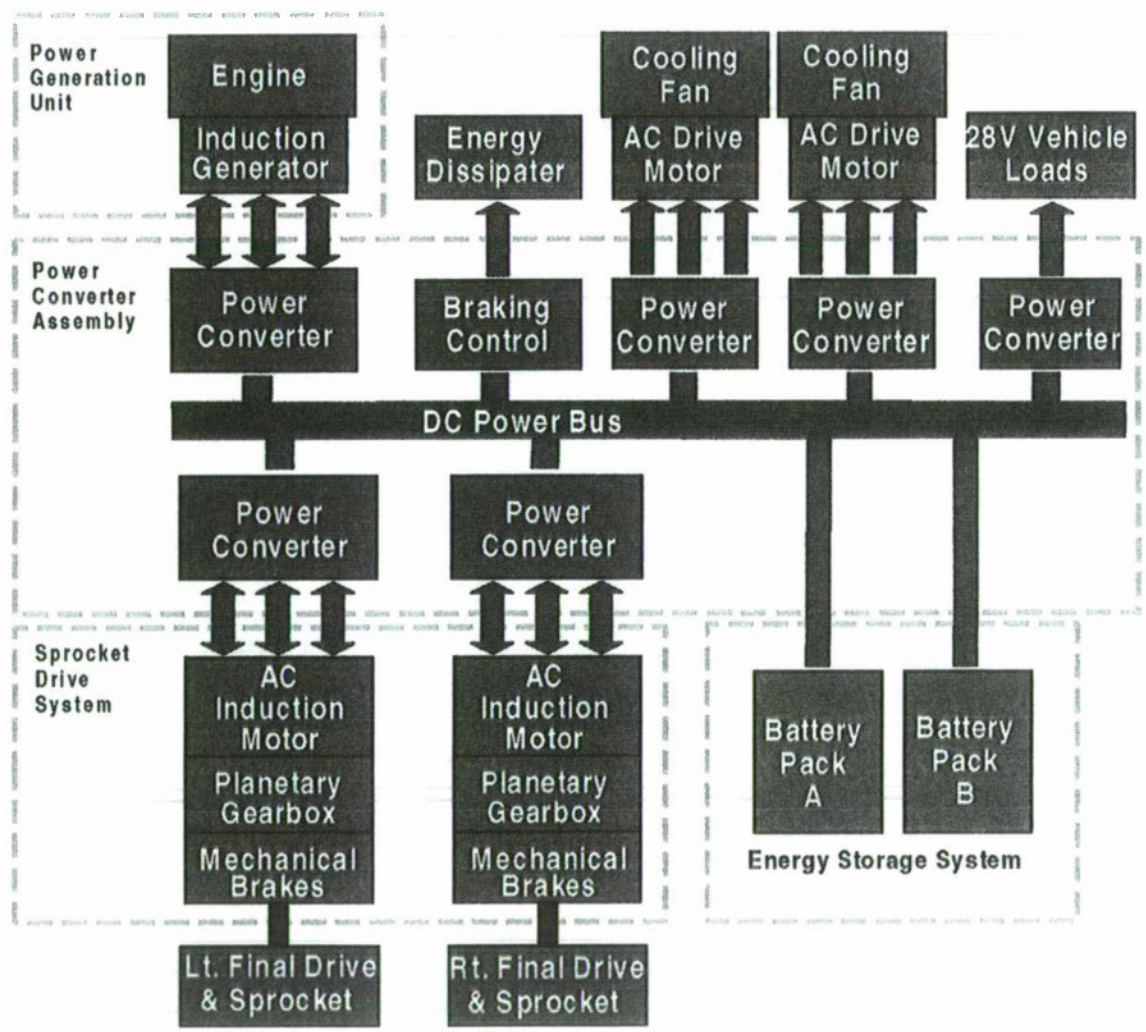
United Defense

DARPA TARDEC



Power Distribution Architecture and Overall Specifications

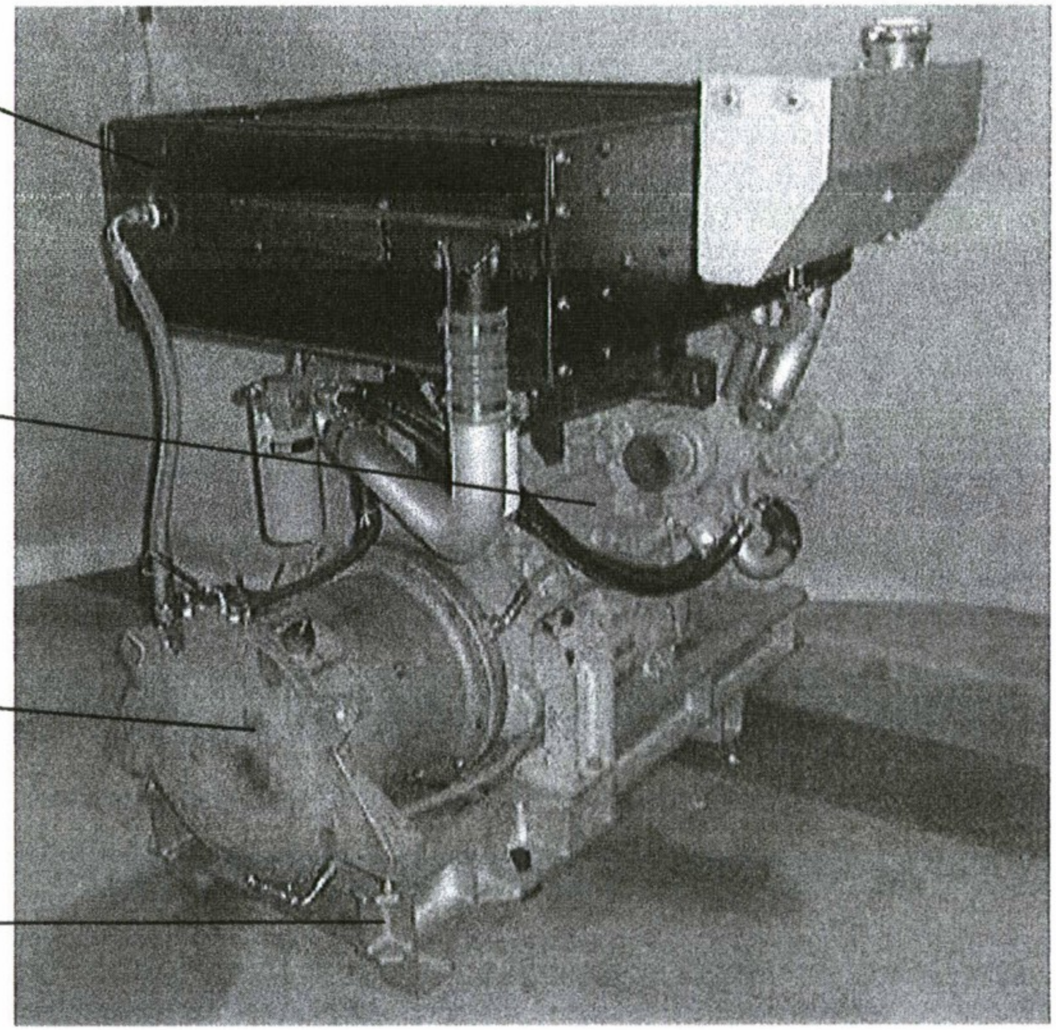
- **General Specifications:**
  - Vehicle Type: BFV-A0
  - GVW: 50,000 lbs.
  - Drive Motors: (2) AC Induction, 410 kW each
  - PGU: Diesel-based, 300 kW
  - Generator: AC Induction
  - Bus Voltage: 528 VDC (nominal)
- **Common DC Power Bus used to link all power producers and consumers**
- **Engine-Generator used to supply "average" power demand**
- **Stored energy (battery pack) used to supply transient power demand — superior acceleration, hill climbing, and steering**
- **Regenerated braking energy directed to batteries — increased range and fuel economy**
- **Generator used to crank engine and to back-drive engine to absorb excess braking power**



Power Generation Unit

United Defense

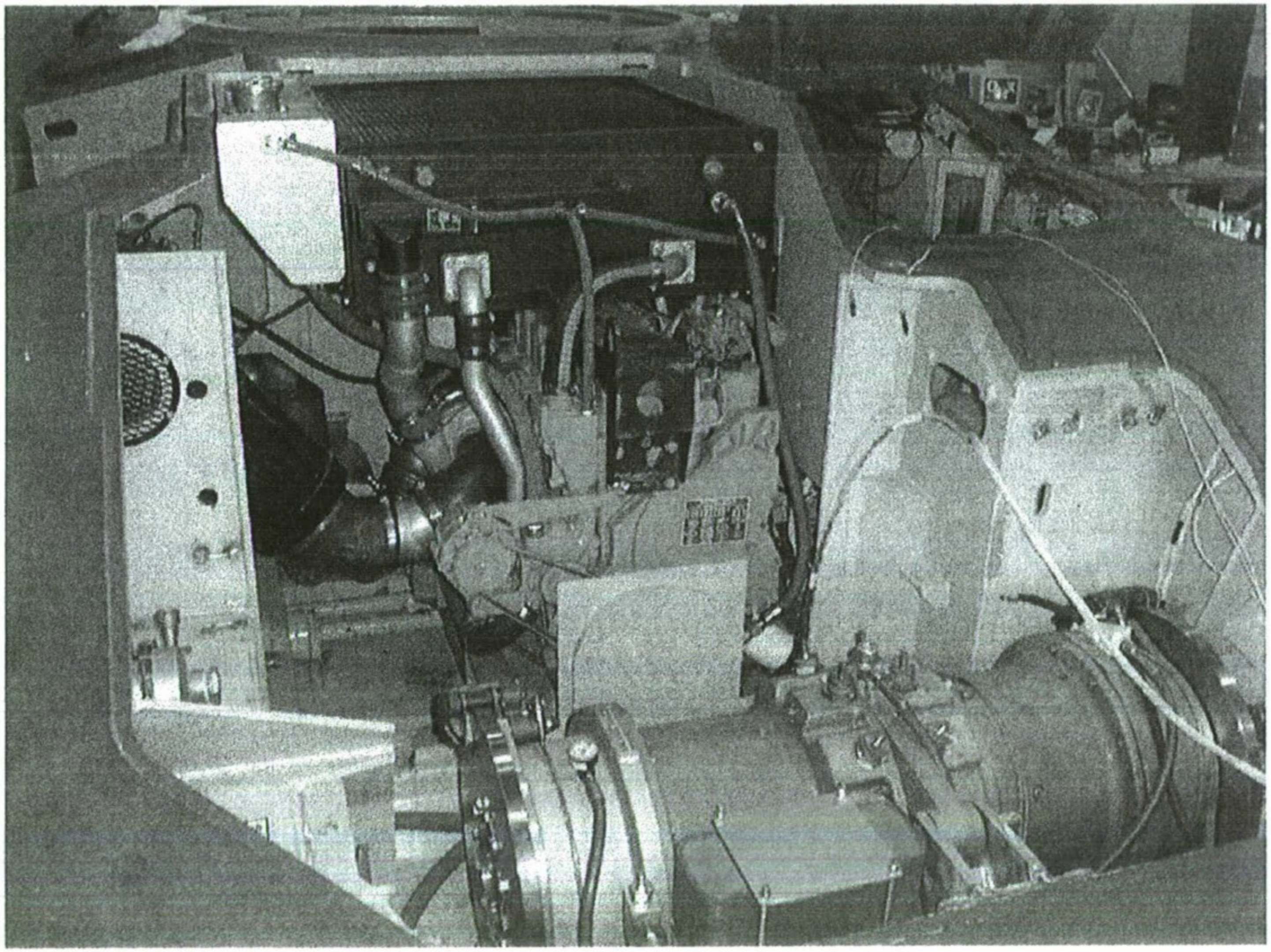
- **Heat exchangers mounted on engine for ease of maintenance**
  - Low-temperature water cooler
  - Aftercooler
  - Oil cooler
  - Engine radiator
- **Caterpillar 3126 Inline 6**
  - 300 kW @ 2600 rpm
  - Turbocharged and aftercooled
  - Electronic fuel injection
  - J-1939 databus interface
- **Direct Drive Induction Generator**
  - Acts as engine starter
  - Backdrives engine during braking
- **All components mounted on subframe for easy "ground-hop" operation**



Power Generation Unit Integration

United Defense

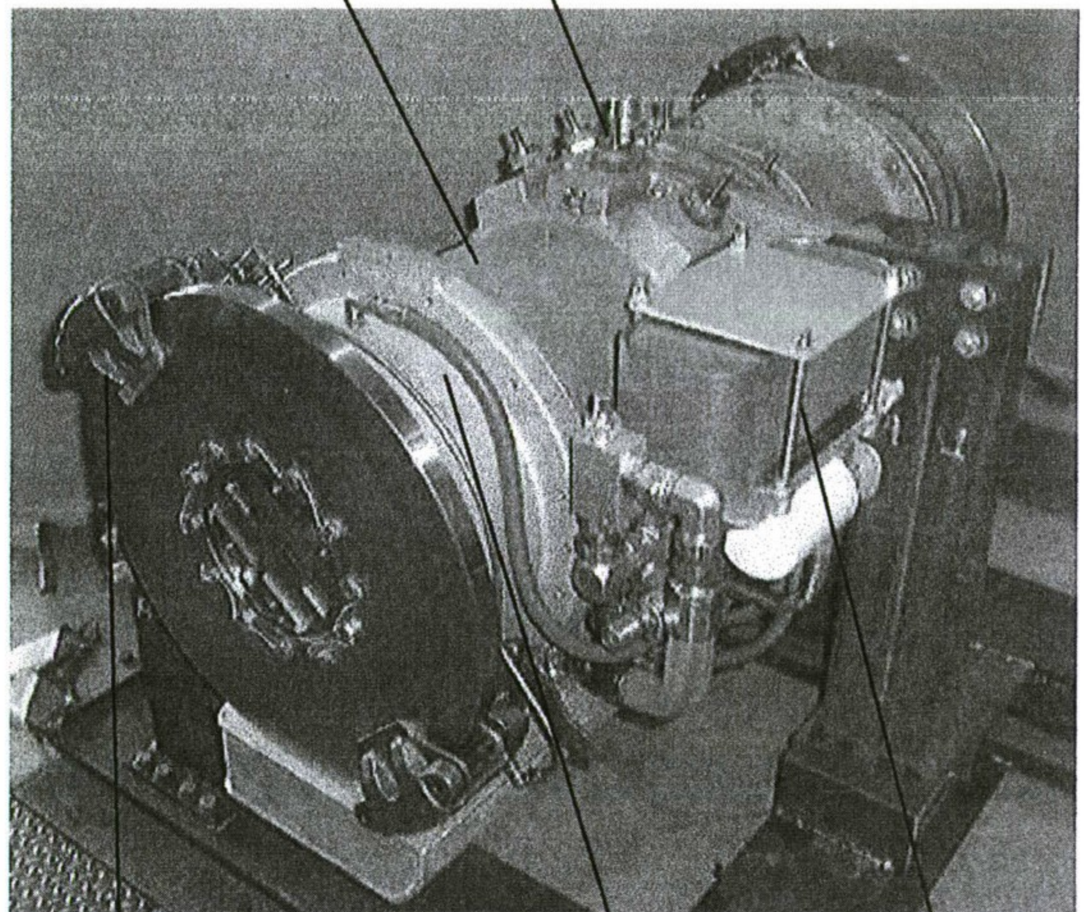
DARPA TARDEC



United Defense

Motor Package Features (2) Independent Motors with Planetary Gearboxes and Backup Mechanical Brakes

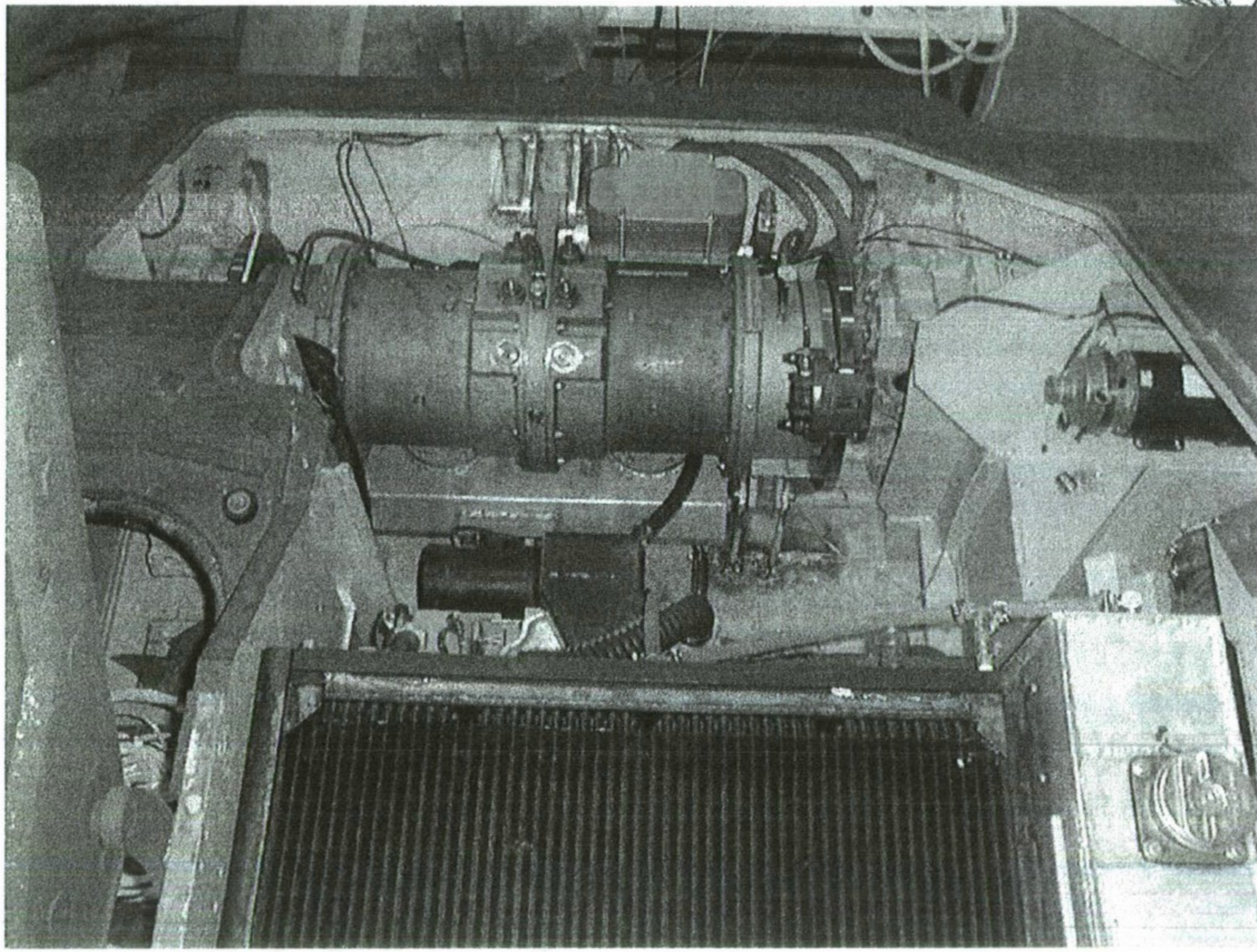
- Dual 3-phase AC induction motors joined with common center housing
- High speed (14,000 RPM rated) for wide torque/speed range
- Oil cooled rotor and stator for maximum torque density
- Package includes 4.4 : 1 planetary gearbox to match torque/speed requirements of BFV vehicle
- Includes mechanical / hydraulic parking and backup brakes
- Maximum intermittent torque: 1856 ft-lb at motor shaft. (8,166 ft-lbs at gearbox output) at 2000 A rms per phase
- Maximum continuous torque: 1200 ft-lb at motor shaft with 200°F cooling oil
- Electromagnetic Weight: 465 lbs. per motor
- Total Weight: 1800 lbs.



Sprocket Drive Installation

United Defense

DARPA TARDEC

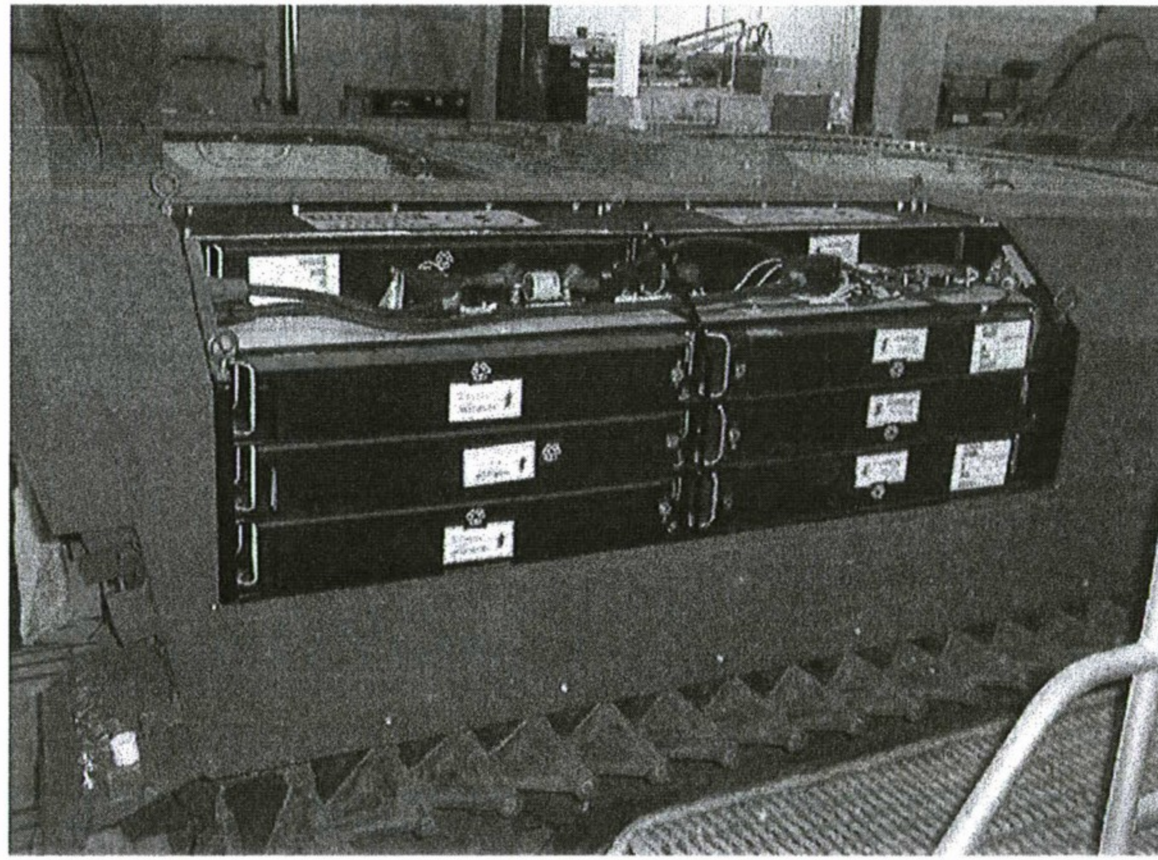


Battery Pack Installation

United Defense

DARPA TARDEC

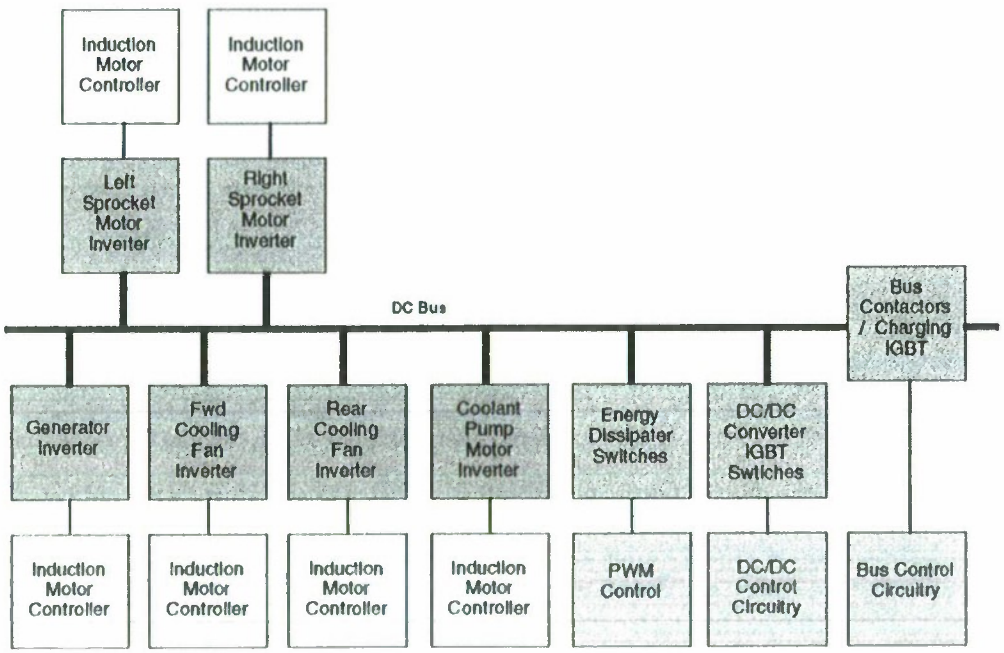
- **Battery Packs**
  - Two (2) parallel strings
  - 44 Modules in series
  - Forced-air cooled
  - Charged by
    - » High voltage dc bus
    - » On-board battery charger (5 kW)
- **Electrosource 12N85 modules**
  - Sealed lead acid
  - 12 Volt
  - 85 A-Hr C/3 @ 25°C
  - 24.9 kg each

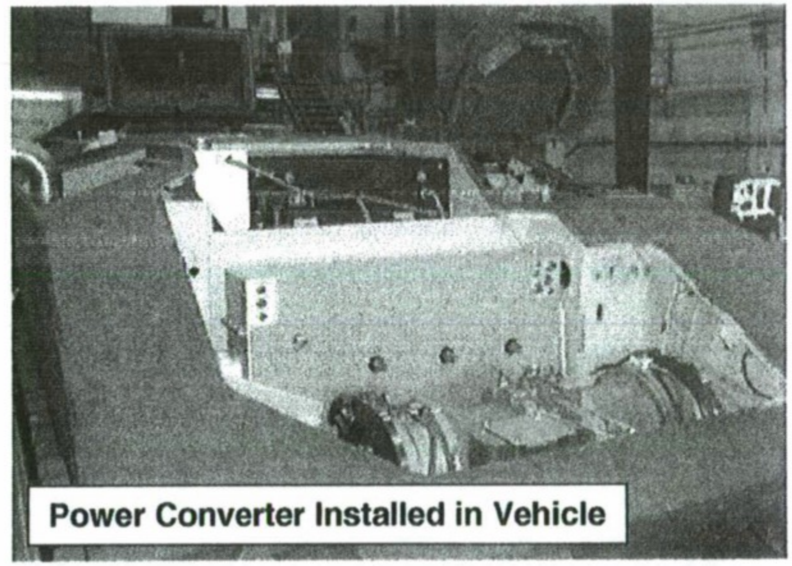


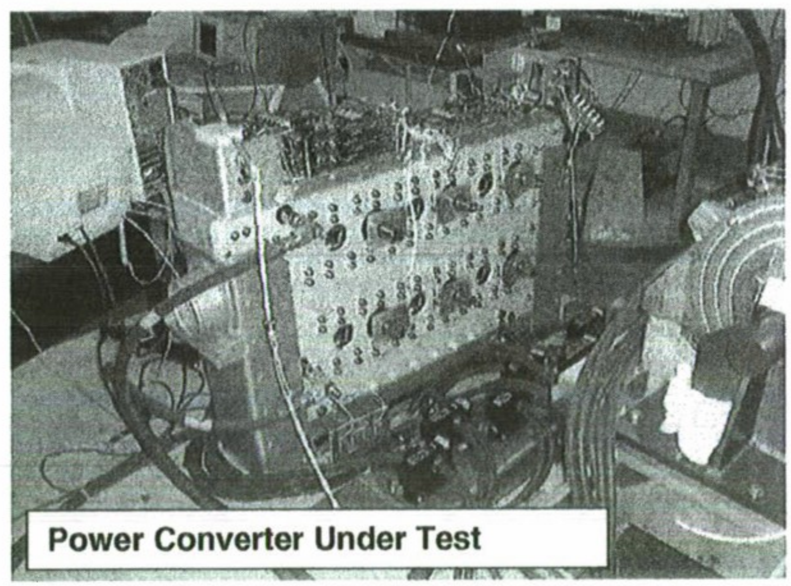
Integrated Power Converter Assembly

United Defense

- 2000 amps rms per phase for each (3) phase sprocket drive motor inverter
- Maximum input voltage 700 VDC
- Weight: 325 lbs. Size 46.0 L x 30.0 H x 12.0 W
- Liquid-cooled with 165°F WEG
- All subsystems are integrated within a single power and control electronics assembly:



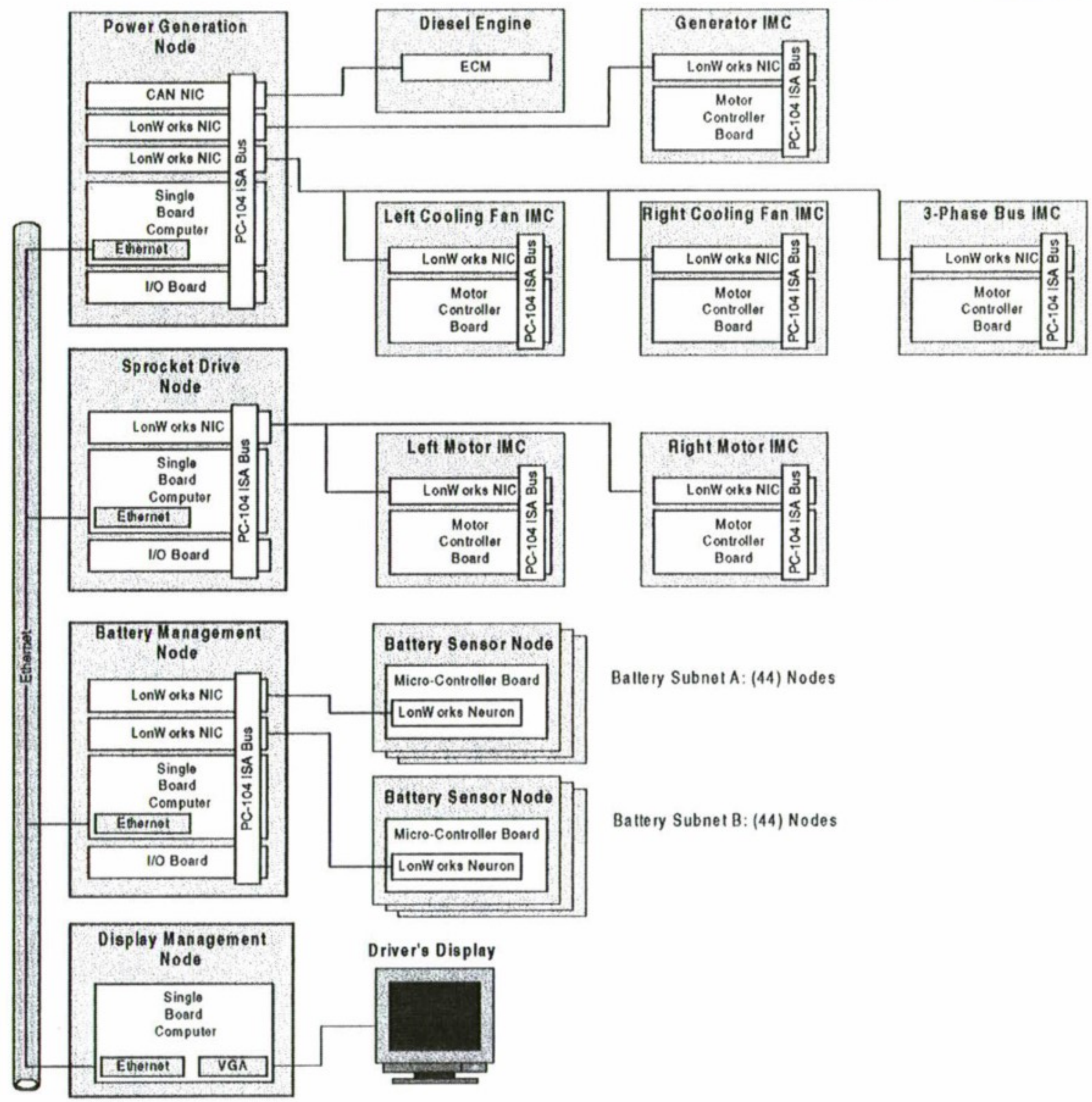




United Defense

Vehicle and Power Management Controller Features
Distributed Processing and Control Nodes

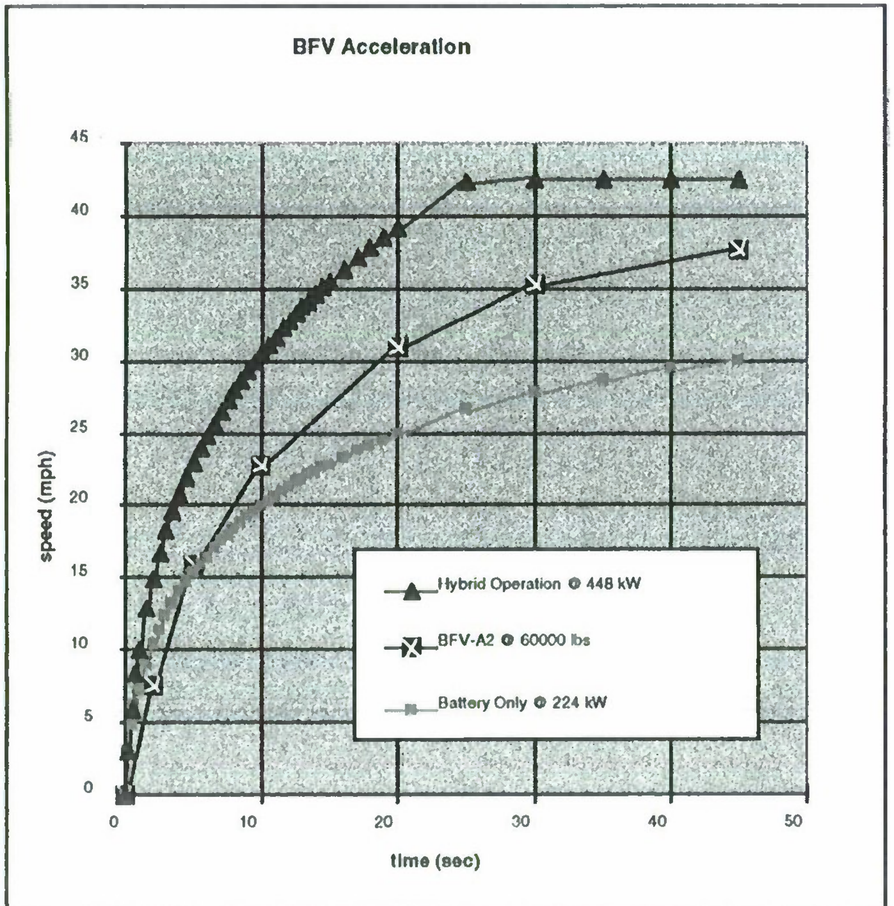
- Low-cost computing nodes connected with high-speed Ethernet databus
- Driver's information and diagnostic data through VGA-compatible display
- Schedules operation of engine to provide most efficient power generation
- Directs regenerated power to energy storage system and to backdrive engine and/or power cooling fans.
- Temporarily reduces parasitic loads to increase power for acceleration.
- Extends battery life by controlling charge / discharge rates and depth.
- Controls stationary recharging of batteries and provide module charge balancing

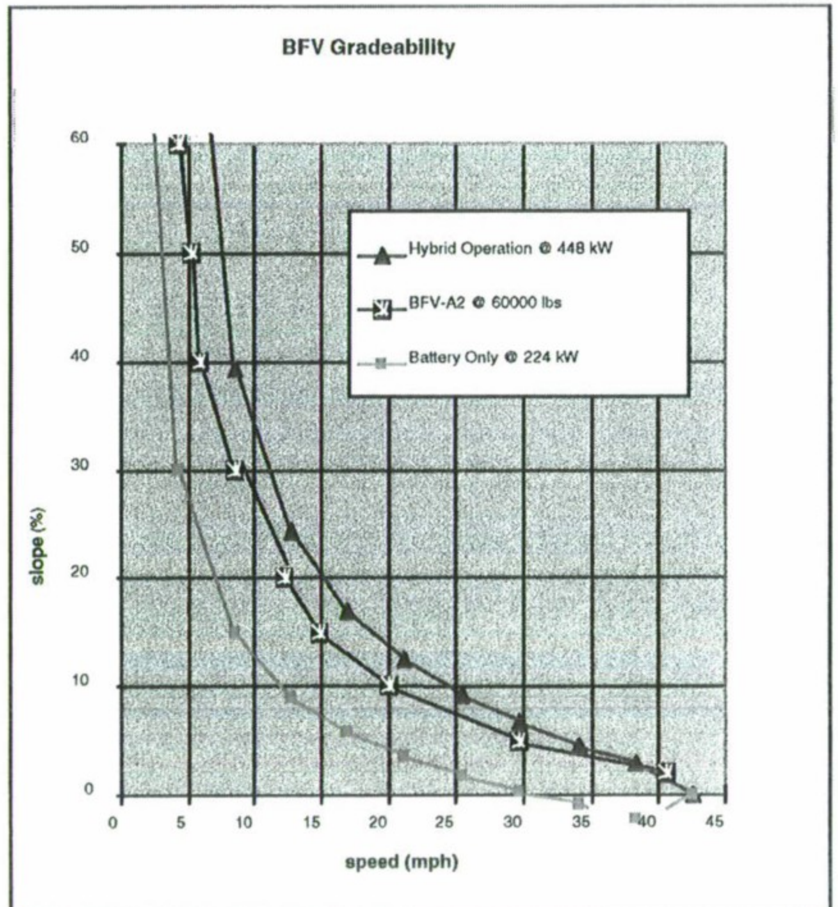


HED-BFV Automotive Performance Goals

United Defense

DARPA TARDEC





Vehicle will be operational in June 1999

- **Perform Contractor Testing**
  - Dynamometer Building
  - Test Track in San Jose
  - Camp Roberts, CA Test Site
- **Demonstrate benefits of hybrid electric drives**
  - Faster acceleration
  - Greater fuel economy
  - Reduced noise and thermal signatures
  - Stealth operation (silent mobility)
- **Evaluate advances in electric drive technology**
  - High power density drive motors and power conversion hardware
  - Component and system cooling approaches
  - Power/Energy control algorithms
- **Ship vehicle to Aberdeen Proving Grounds for Government testing in January 2000**

HYBRID RECONNAISSANCE, SURVEILLANCE, TARGETING VEHICLE (RST-V)

1999 Vehicle Technologies Alternative Propulsion Symposium

5 May 1999

Presenters: Tom Trzaska
Manager, Developmental Programs; GDLS

Jeff Bradel
Project Manager, Marine Corps Programs; NSWC - Carderock

AGENDA

- USMC Challenge
- RST-V Program Overview
- RST-V Propulsion System
  - Enablers
  - Key Subsystems
- Summary

USMC CHALLENGE

- Findings from OMFTS Implementation Study Group:
  - RSTA is #3 Deficiency
  - Family of V-22 Internally Transportable Vehicles
- MCLLS - MEU(SOC) Deficiency for R/S Capabilities
- Fleet Operational Needs Statement 1999
  - Long Range Ground Reconnaissance Deficiency
- Internally Transportable-Light Tactical Vehicle - *MNS*
- Tactical Vehicle RSTA - *MNS*
- Target Location, Designation, Hand-off - *ORD*
- Light Strike Vehicle (LSV) - *JORD*

USMC CHALLENGE

- Approach
  - Jointly Sponsored by DARPA and USMC
  - Advanced Technology Demonstrator R&D Program
- Objective
  - Design, Build, Test, and Demonstrate Four (4) Platforms:
    - V-22 Compatibility
    - Hybrid Electric Drive
    - Integral Advanced Survivability
    - Performance > HMMWV
  - Evaluate During Advanced Warfighting Experiments and User Demonstrations

OPERATIONAL CONCEPT

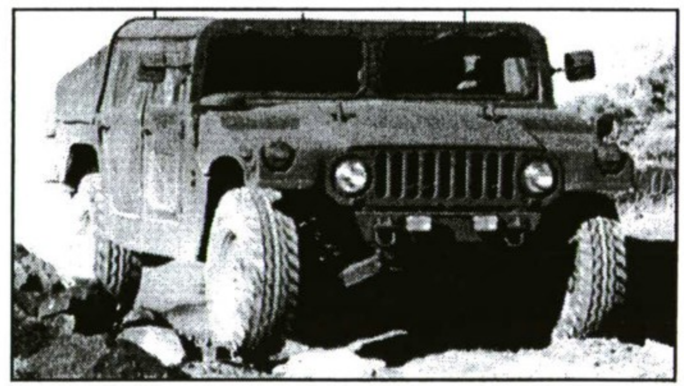
- V-22 Internal Transport
  - Deployment Ready
  - Tactical and Deep Insertion
  - 10 Day Mission
- Integrated Survivability
  - Ballistic
  - AP Mine
  - Managed Signature
- Mission Tailorable
  - RST
  - C^4I
  - Agility
  - Weapons

All In An Affordable Package

SHORTCOMING OF EXISTING SYSTEMS

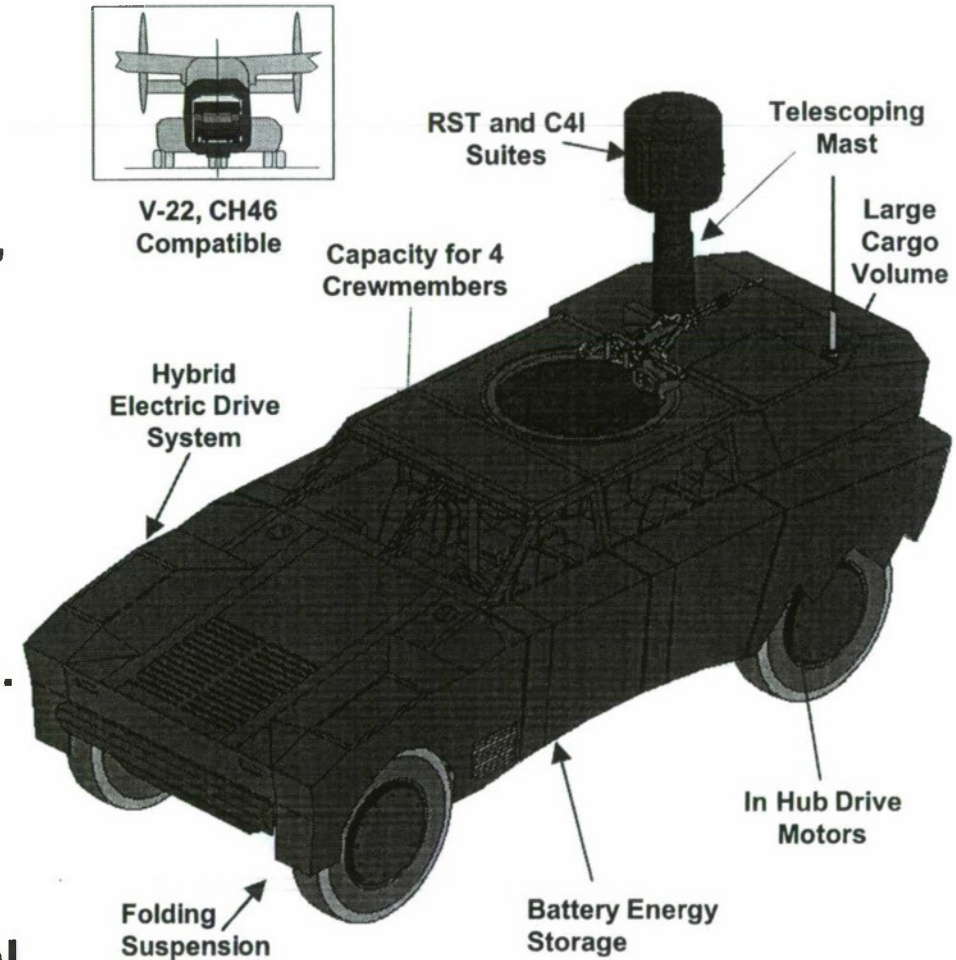
- Fast Attack Vehicle, M-151 Series
  - Unstable Due to High Center of Gravity
  - No Longer Supportable Due to Unavailability of Replacement Parts
  - Uses Gasoline
  - Limited Operational Range, 125 Miles
  - Limited Mobility vs. HMMWV

- HMMWV
  - Limited Transportability
  - Will Not Fit in Most Helos or V-22
  - Poor Fuel Economy
  - Not Suited for Silent Movement / Silent Watch



KEY RST-V FEATURES

- GDLS RST-V Design Meets Operational and Demonstration Objectives:
  - Increased All Terrain Mobility, Agility, Acceleration
  - Improved Fuel Economy and Range
  - Silent Watch and Auxiliary Power Capability
  - Payload Same as HMMWV
- Solves V-22 Vehicle Width vs. Lateral Stability Problem
- Realizes Full Potential of Hybrid Electric Drive
- High Future Growth Potential



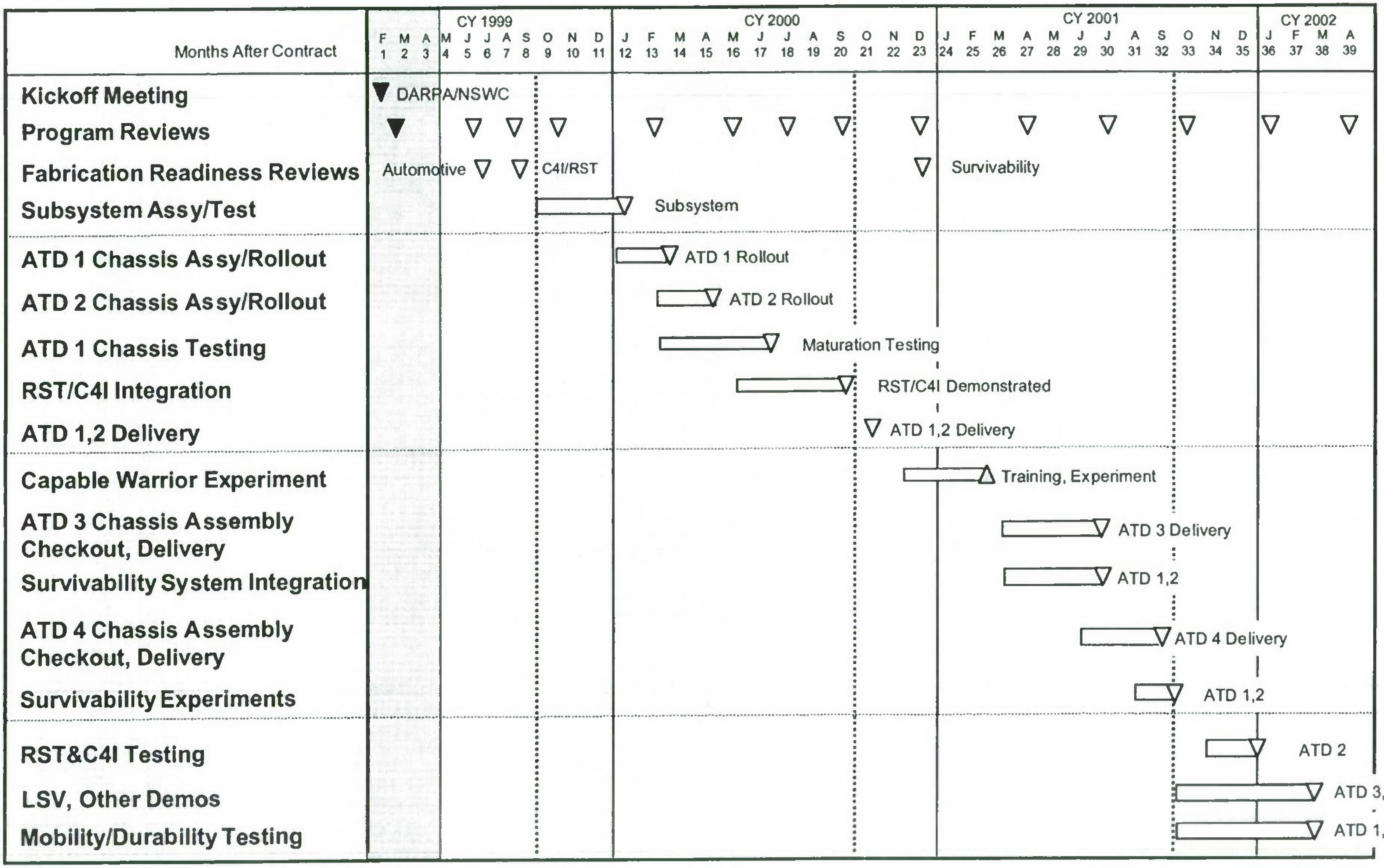
GDLS Design is High Payoff in Military Utility *and* Growth Potential

PROGRAM SUMMARY

- SPONSORS
  - DARPA
  - USMC (Through NSWC-Carderock Div.)
- PERIOD OF PERFORMANCE:
  - January 1999-April 2002
- OBJECTIVE
  - Design, Build, Demonstrate and Evaluate Advanced RST Vehicle with
    - Hybrid Electric Drive
    - V-22 Compatibility
    - Integral Adv. Survivability
    - Performance $\geq$ HMMWV
- MAJOR DELIVERABLES
  - 2 Demonstrator Vehicles
  - 2 Baseline Vehicles
  - Test Support, Spare Parts
  - Design Documentation, Data

POC's: Art Morrish,	Govt. Program Manager	703-696-7502
Jeff Bradel,	Govt. Technical Lead	301-277-4222
Rick DuVall,	Program Manager	616-780-5510
Bob Hoeltzel,	Chief Engineer	616-780-5571

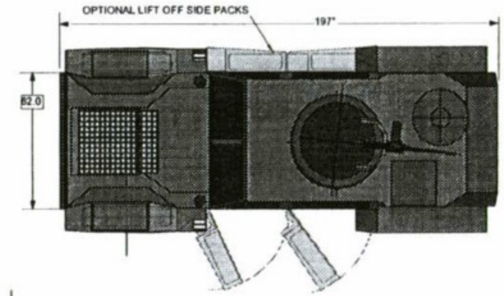
RST-V PHASE II SCHEDULE

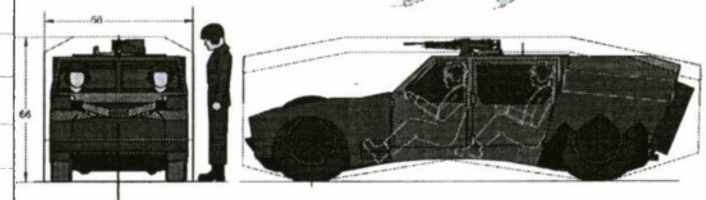


RST-V PERFORMANCE

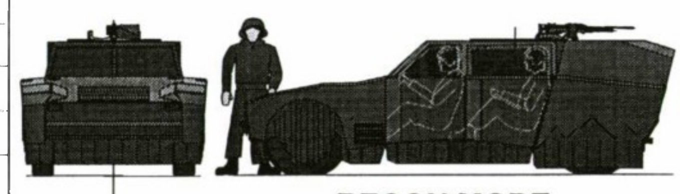
CHARACTERISTICS	RST-V	HMMWV (M1025A2)
Gross Vehicle Weight	8000* lb.	10300 lb.
Payload	**3000 lb.**	3520 lb.
Air Transport - Internal roll on/roll off	**V-22, CH53, C-130**	C-130
Range - Engine (25 gals fuel) highway, 30 mph	**490 mi.**	270 mi.
Range - Batteries (Highway)	**25 mi.**	na
Relative Fuel Economy (scenario dependent)	**1.7-2.0 X**	Reference
Fording Depth	36 in.	36 in.
Gradeability /Side Slope	60%/40 %	60%/40%
Top Speed Hwy.	70+ mph	70 mph
Ride-limited speed, rough cross country	**~18 mph**	~12 mph
0-30 mph Acceleration	**~3.0 sec.**	9.4 sec.
0-60 mph Accel. (HMMWV 0-50 mph)	**15 sec.**	25+ sec.
VCI - off road (25% deflection)	**19.8**	20.2
Ground Clearance	**4 - 24 in.** (variable)	16 in.
Amphiblous option	**Adaptable**	no

* 10,000 lbs with reduced performance



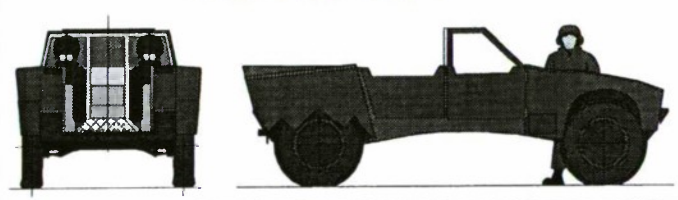


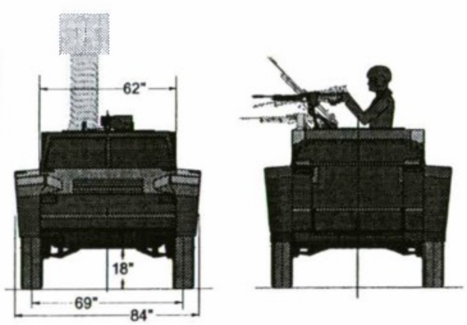
V-22 TRANSPORT PROFILE

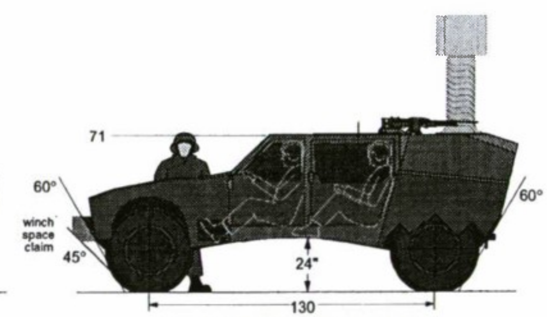


RECON MODE

BASELINE RST-V

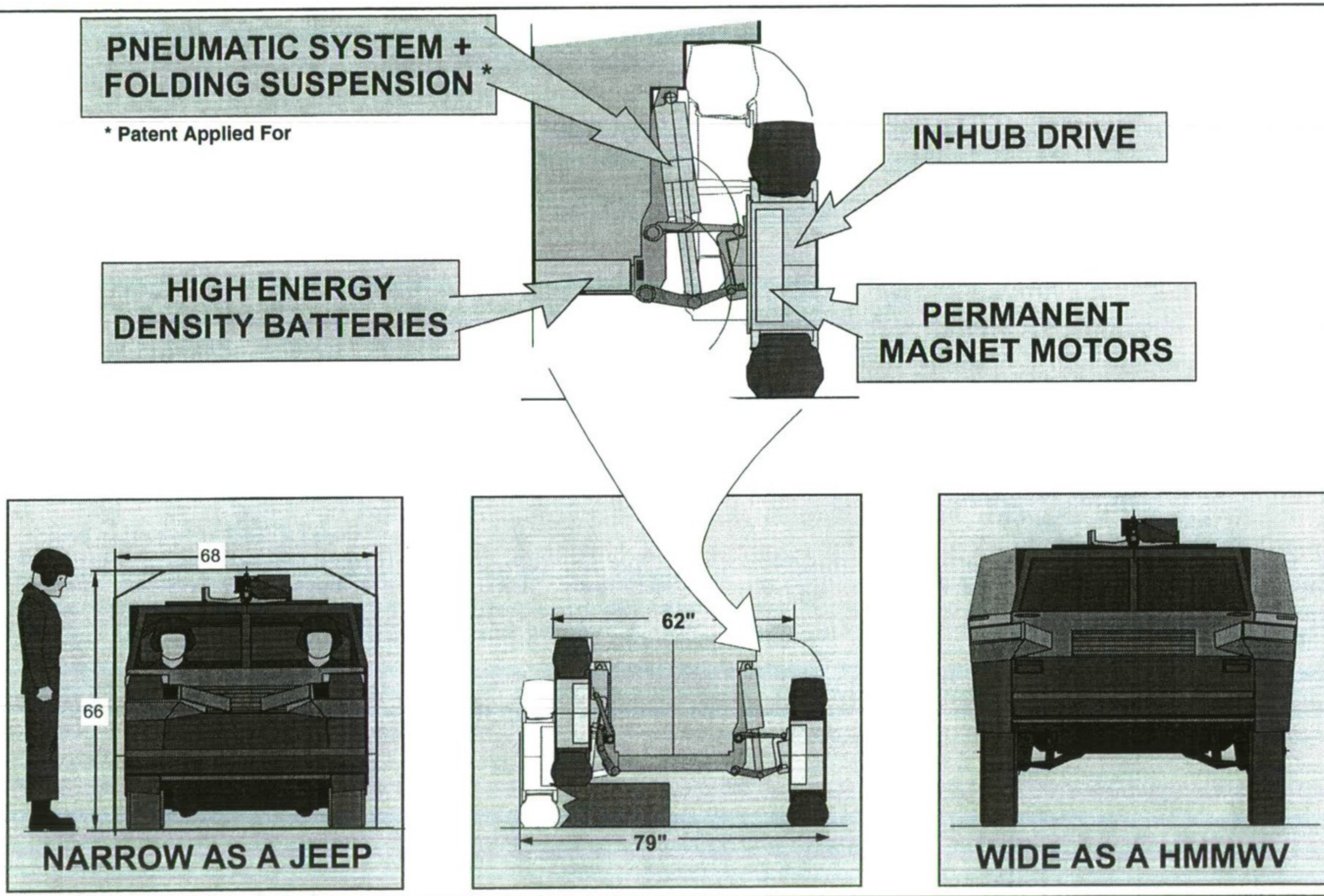






CROSS COUNTRY

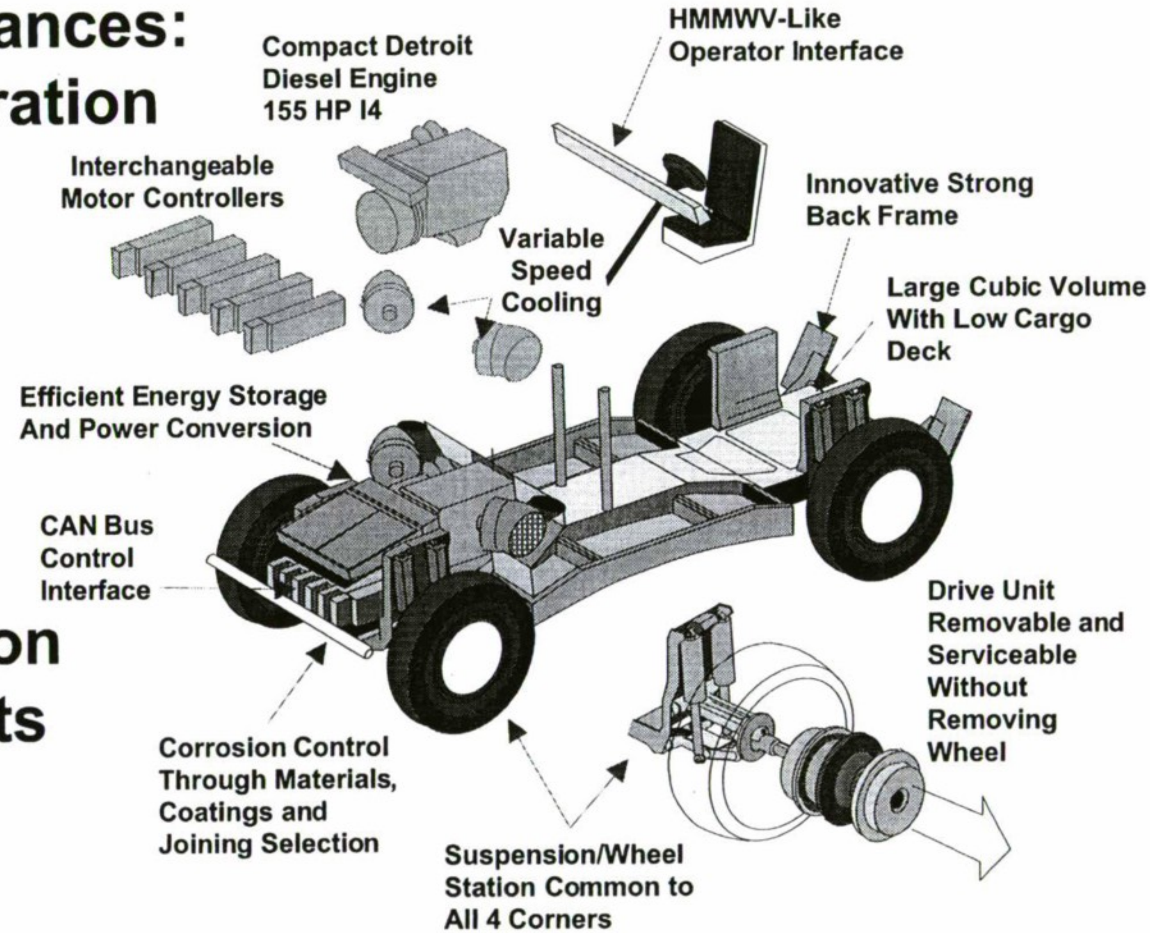
KEY ENABLING TECHNOLOGIES



MODULAR DESIGN APPROACH

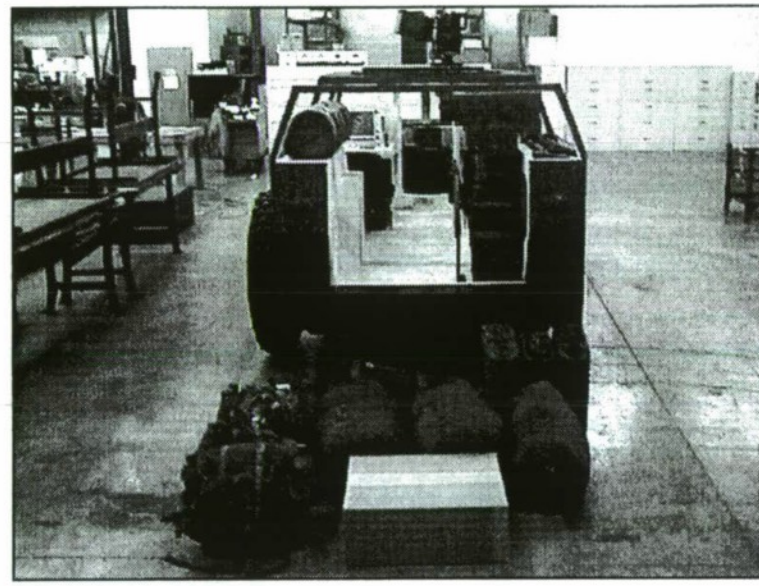
- Modular Design Enhances:
  - Development Maturation
  - Maintainability
  - Supportability
  - Survivability

- High Growth Potential:
  - Technology Insertion
  - Economical Variants
  - Mission Module Integration



RST-V OPERATIONAL SUITABILITY

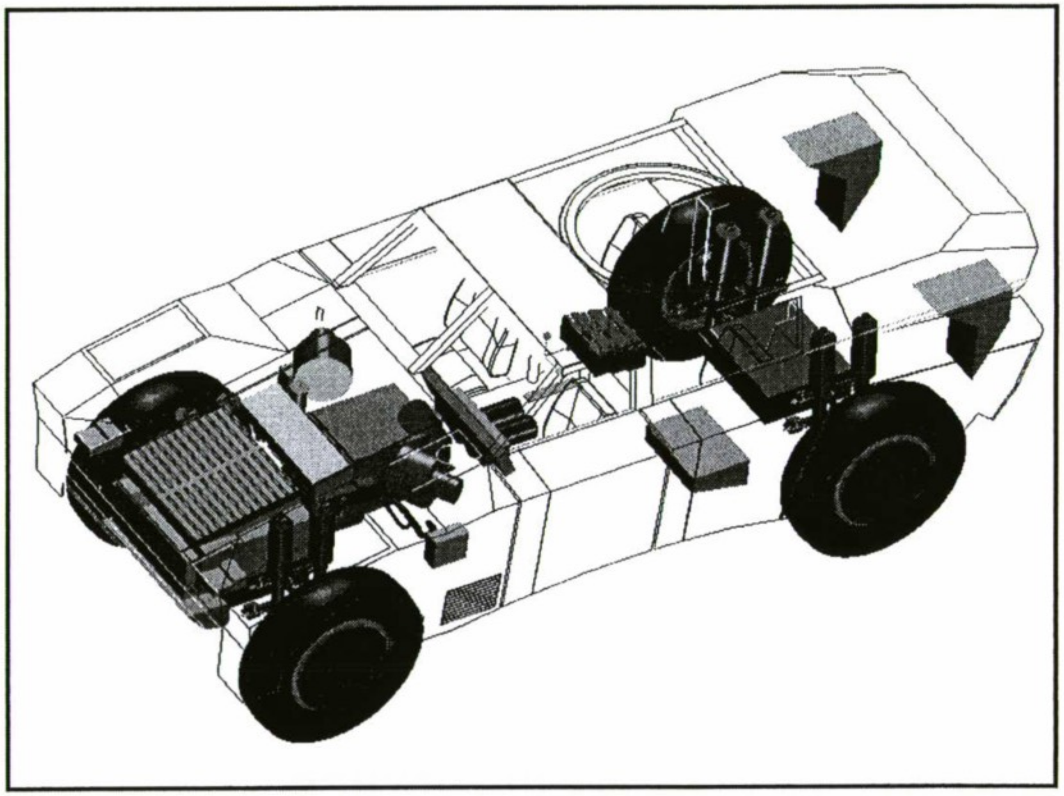
- Mock-Ups Utilized to Validate Design Utility
  - Man/Machine Integration
  - Cargo Capacity
  - Weapon Integration



- Maintainability Approach Validated
  - Modular Architecture
  - Wheel Stations

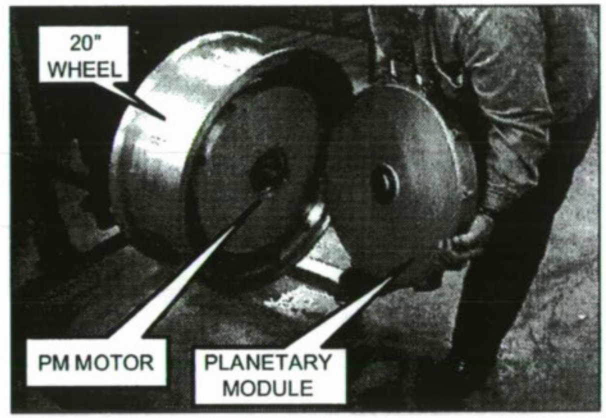
PROPULSION SYSTEM

- Engine
  - DDC DI-4V, 2.5 liter, 155 HP
- Generator
  - Magnet Motor 110 kW Permanent Magnet
- Batteries
  - Saft Li-Ion, EV Batteries
  - 2 Packs, 20 kWh Total.
- Motor/Generator Control
  - 3 Phase, H Bridge, PWM
  - IGBT Based
- Drive Motors
  - Magnet Motor 50 kW Permanent Magnet
- Cooling
  - WEG, Oil Loops



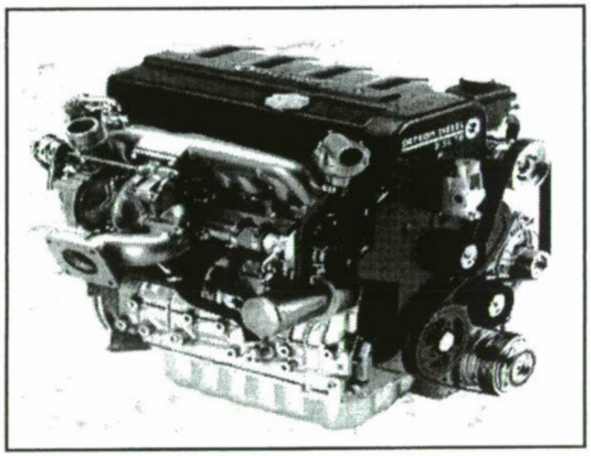
RSTV Energy Management and Propulsion Systems Components

KEY SUBSYSTEMS



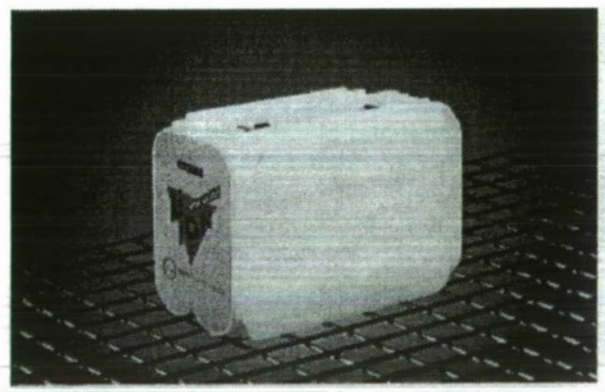
Wheel Drive Unit

- MM Permanent Magnet Motor
- Modular Design
- Push Start With Dead Batteries
- Torque 3660 Nm (Peak) 3030 Nm (Continuous)
- Wheel Gear Ratio 5.07:1



IC Engine

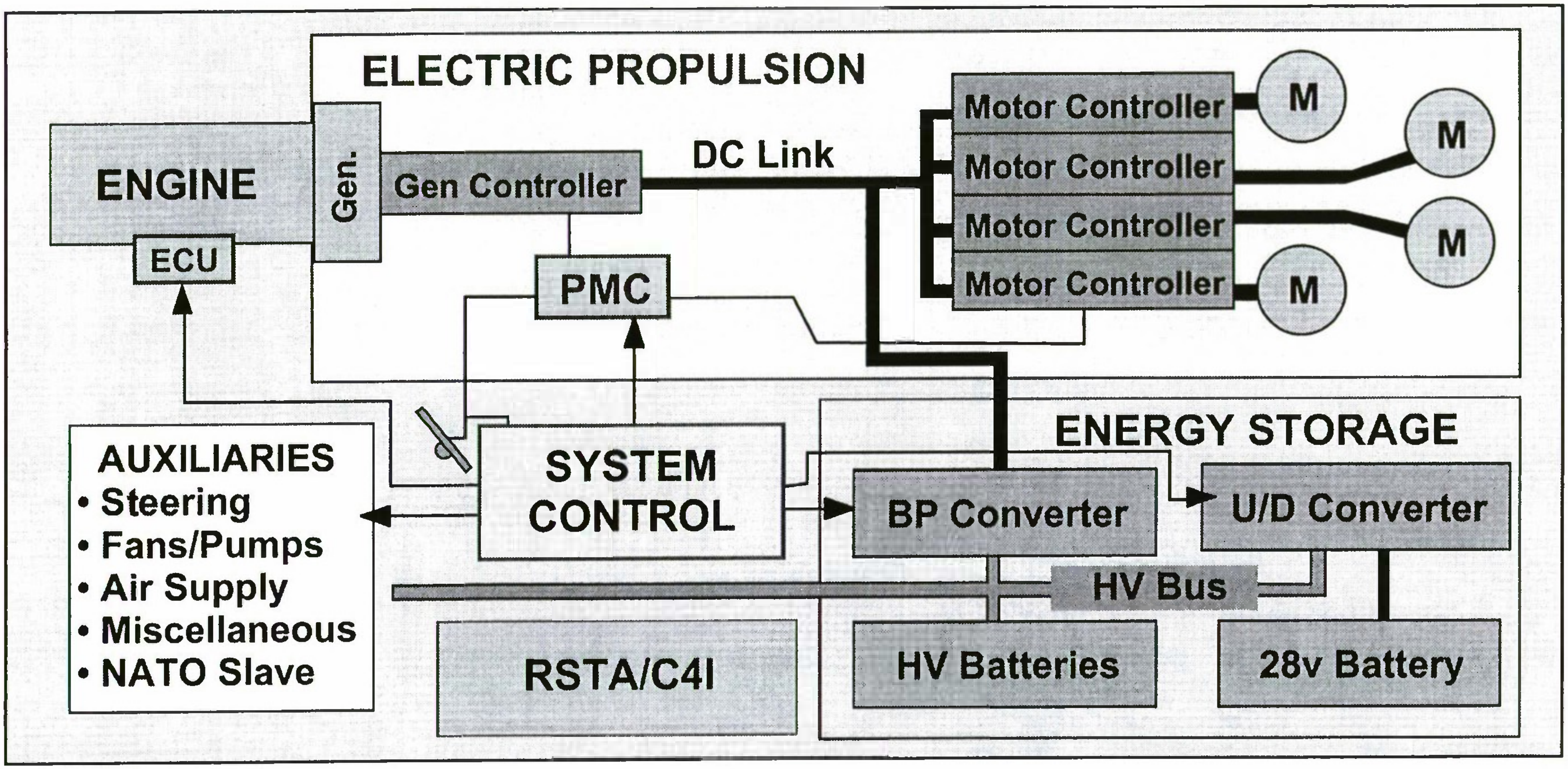
- DDC TD DI-4V, 2.5 liter, 114 kW
- Common Rail Direct Injection Diesel
- Turbocharged, Intercooled
- Meets EURO 3 Emissions Requirements
- 207 gr/kW hr. BSFC



Energy Storage

- Saft Lithium-Ion Battery Technology
- EV Optimized Battery Chosen for Application
- 2 Packs, 240 V, 10 kWh Each
- Burst Power 90 kW

RST-V ELECTRICAL ARCHITECTURE



- Robust
- Degraded Operation Modes
- Flexible, Expandable
- Life Cycle Cost Advantage
- Technology Insertion
- P3I Paths

OPERATING MODES

Normal

- Hybrid Drive Powered by Generator and HV Battery

Recon

- Powered by HV Battery, OR
- Powered by HV Battery and Engine, With Engine Running at an Optimum Power Level

Fuel Economy

- Power Limited to Optimum Fuel Economy Power Level

Silent Watch

- No Mobility
- Absolute Minimum Power Consumption
- Power Supplied by HV Battery
- Charging Available by Operator Command

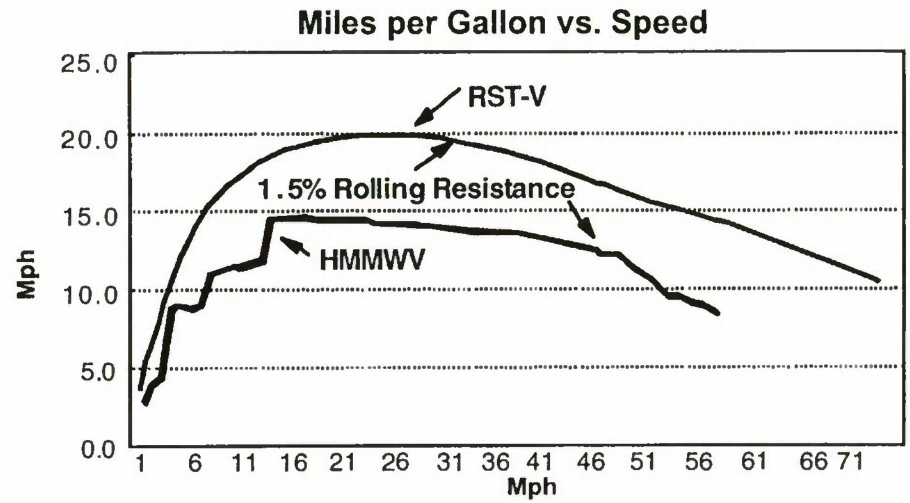
Auxiliary Power

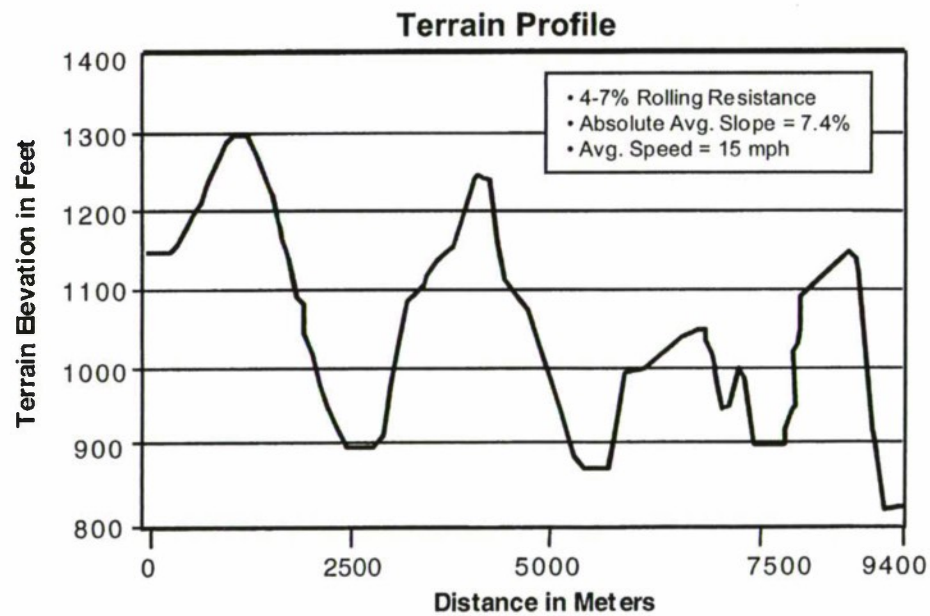
- Stabilizes The DC Link at 480V, ~85 kW, Assumes External Power Conditioning

FUEL ECONOMY

- **The RST-V HEV Will:**
  - Provide Over 20 mpg on Hard Surface
  - Provide Double HMMWV Mileage at Slow Speeds
  - Meet 5 km Silent Movement Requirement with >20 Hours Silent Watch Capability

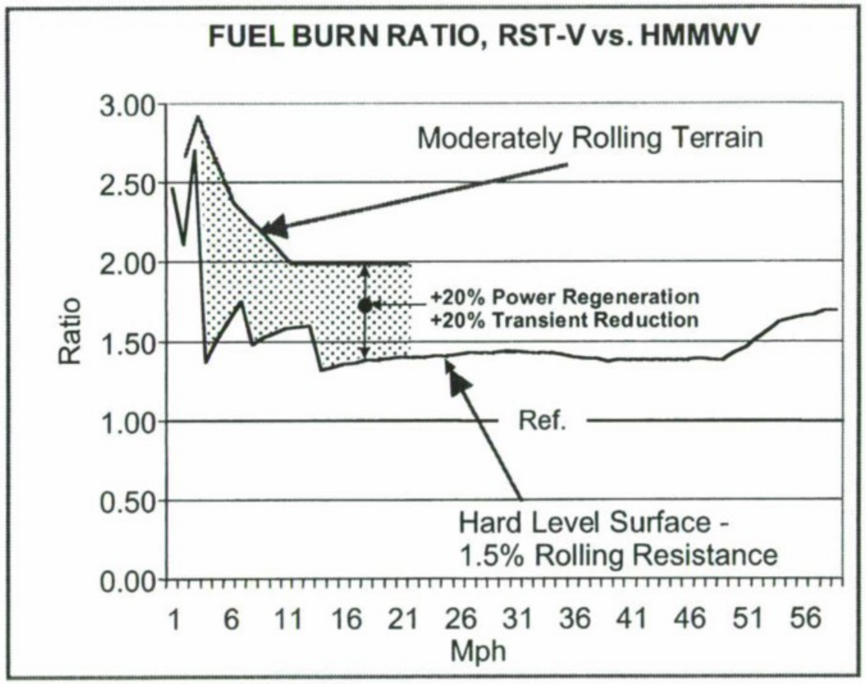
- **Dynamic Simulation Evaluates Off-Road Performance**
  - 18km Mission Profile Created
  - Regenerative Braking and System Energy Management Optimization
  - RST-V Achieves 10.8 mpg on This Profile





HYBRID ELECTRIC DRIVE PAYOFFS

- Improved Fuel Economy
  - Energy Storage
  - Power Regeneration
  - Optimum Engine Operation
- Burst Power (~2 Times Base Engine)
- Extended Silent Watch (>20 Hours)
- Battery-Only Operation (~25 Miles)
- Redundant Power (Engine or Batteries)
- Abundant Aux. Power, No APU Needed
- Remote Control Option
- With In-Hub Wheel Drive:
  - 4x Drive Train Redundancy
  - Maximum All-Terrain Traction
  - Fail-Safe Torque Limiting
- Lowered Engine Stress and O&S Burdens

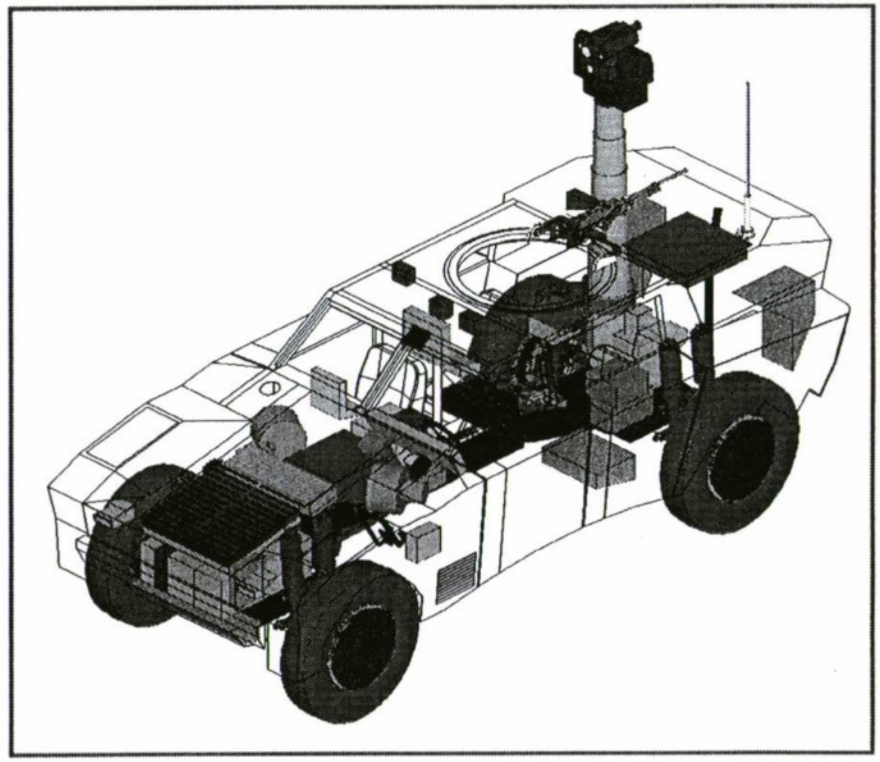


RST-V Fuel Efficiency Consistently Exceeds HMMWV By 1.4x, And Up To >2.5x (At Low Speeds)

FUEL ECONOMY + REDUNDANCY + BURST POWER = A GIANT LEAP AHEAD FOR FORCES IN HOSTILE TERRITORY WITH LIMITED SUPPORT

SUMMARY

- RST-V: Modular Adaptive Design with High Military Utility
- Demonstrates Full Potential of Hybrid Electric Drive
  - Performance
  - Vehicle Architecture
  - Flexibility
- Upcoming Events:
  - FRR; July 1999
  - Subsystem Testing; October - January
  - ATD #1 Rollout; February 2000



RST-V Subsystems Modeled in Pro-Engineer

Hybrid-Electric
Family of Medium Tactical Vehicles
Program

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Lockheed Martin Control Systems
Manager, HEV Business Development
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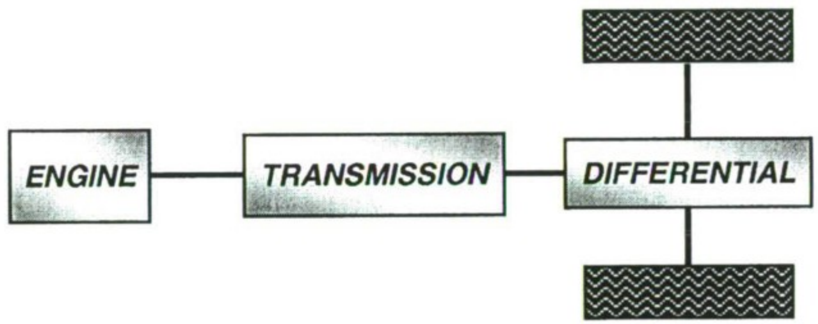
607-770-5751 (fax)
Stephen.Cortese@LMCO.com (email)

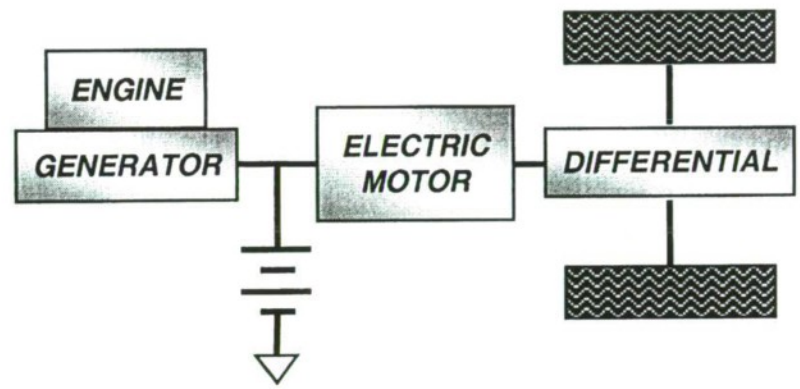
HEV FMTV Presentation Overview

- Architecture Evolution to FMTV
- HybriDrive ™ System Components
- HEV Benefits
  - ⇒ Fuel Economy
  - ⇒ Increased Performance
  - ⇒ Regenerative Braking
  - ⇒ Emissions Reduction
- LMCS HEV Experience
- Dual-Use HEV Roadmap
- Summary/Conclusions

What Is A Hybrid Electric Vehicle (HEV)?



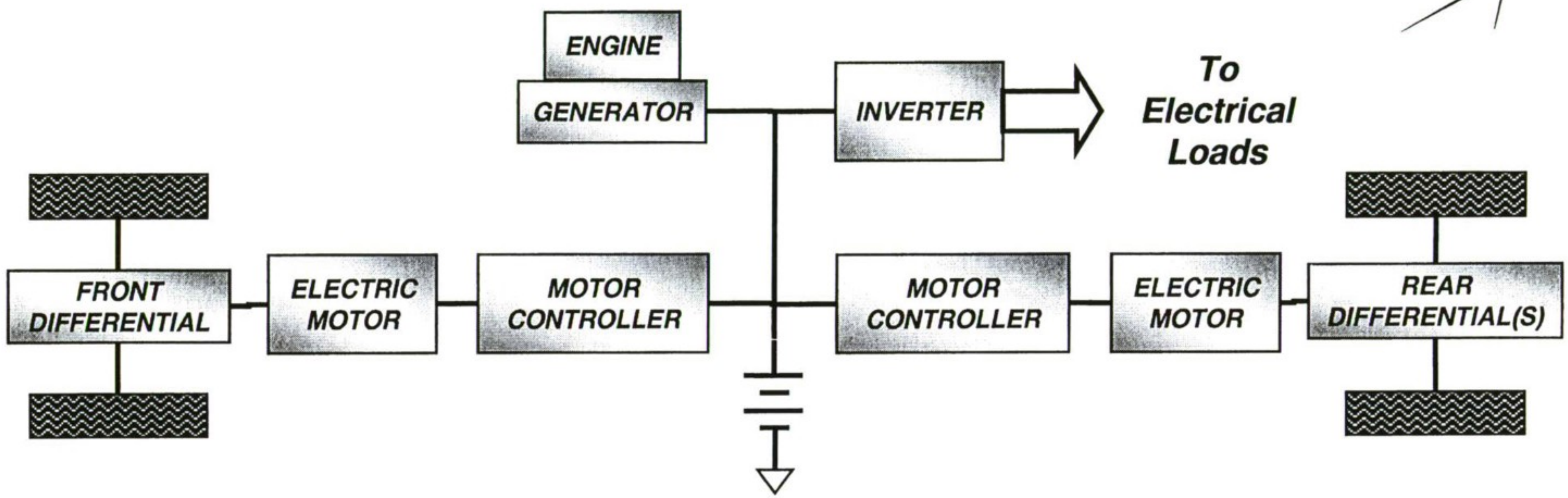
Traditional Drive Train



Hybrid Electric Drive Train

In a Series HEV, Electric Motors Provide All the Propulsion Power Using Energy That Is Provided by Both an Engine/Generator Set and a Battery Pack

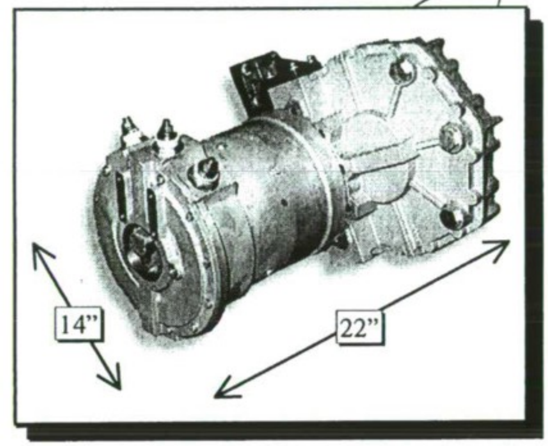
HEV FMTV with Electrical Power Generation



- *Two electric motors are used, one in the front, one in the rear*
- *The engine/generator supplies electricity to the motors for propulsion and the inverter for external electrical loads*
- *The battery stores excess energy from regenerative braking and releases it during vehicle acceleration*
- *Battery energy can be supplied to the inverter for power generation with the engine off (Silent Watch)*

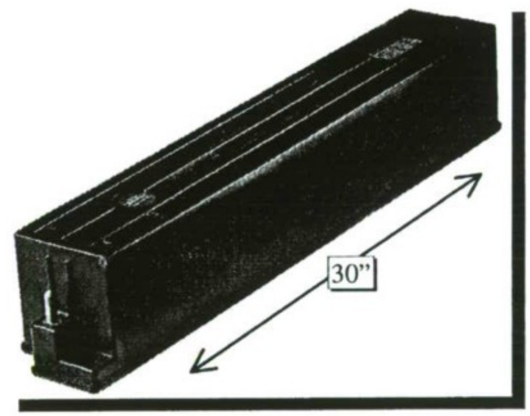
HybriDrive™ Components

AC Induction Motor



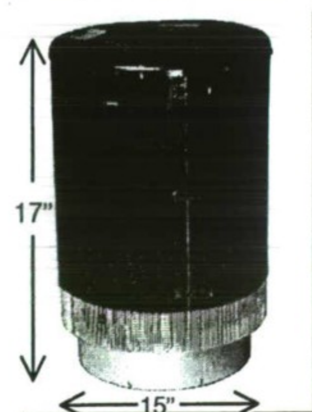
- Designed to Match the Transit Bus Propulsion Requirements
- 250 Horsepower Continuous (320 Hp peak)
- Integral 4.66:1 Reduction Gear Box
- 2100 ft-lbf Continuous Output Torque
- 0 - 3500 RPM Output Speed
- 390 lbs. including Gear Box (Nearly 1 HP per pound)

HybriDrive™ Advanced Lead-Acid Battery



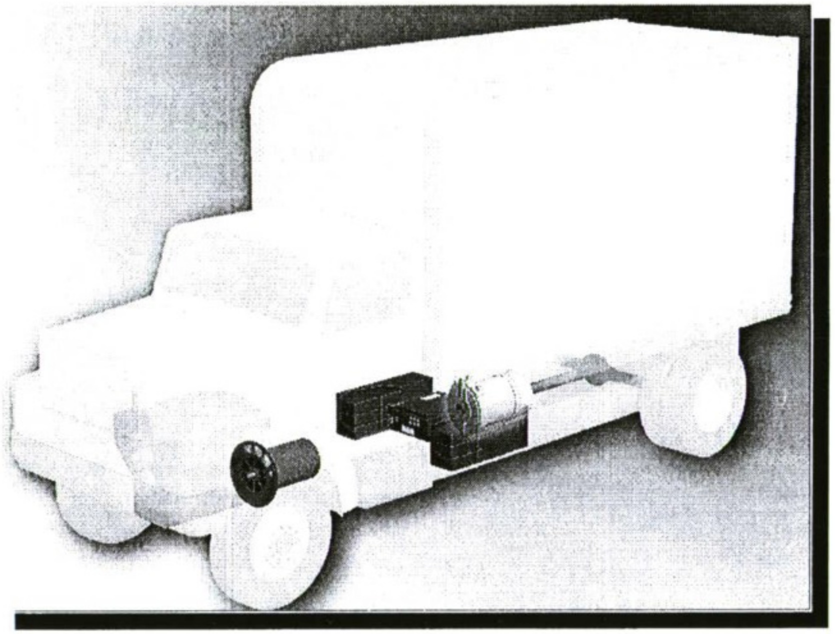
- Absorbed Electrolyte (Maintenance Free, Leak-Proof)
- High Power Density, 440 W/kg (4x Traditional Batteries)
- High Energy Density 45 W-H/kg (2x Traditional Batteries)
- Green Manufacturing Processes, 98% Recyclable

HybriDrive™ AC Generator

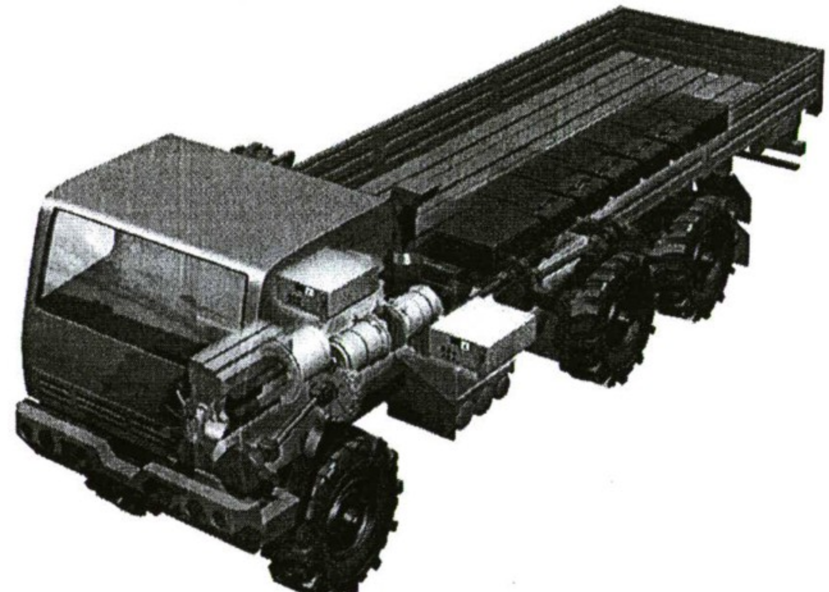


- Designed to Provide Highway Power for Maximum Transit Bus Route Flexibility
- Permanent Magnet Construction
- 120 kW Continuous Output
- Matched To Diesel Engine, Mounts on SAE #2 Flywheel Housing
- Forced Air Cooling

HybriDrive™ Dual-Use Component Layout



Commercial Delivery Truck

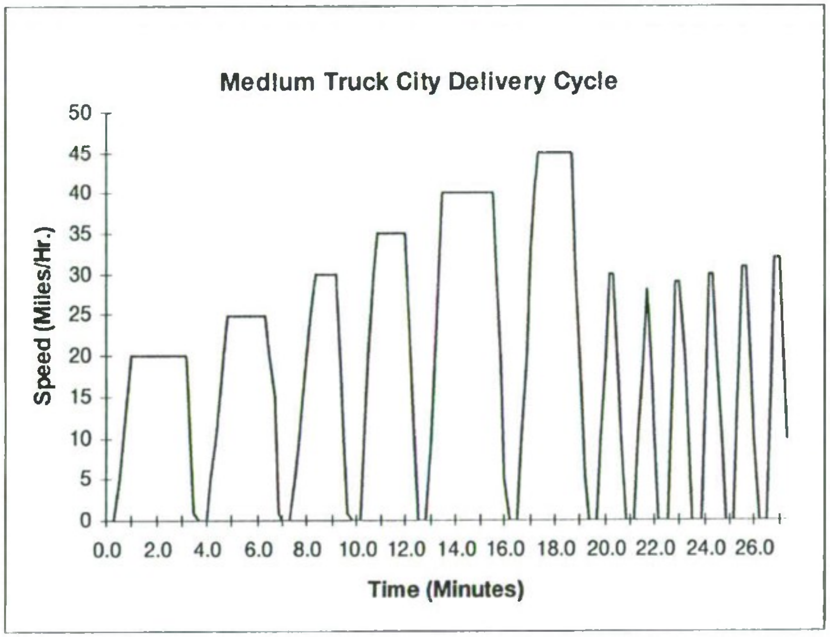


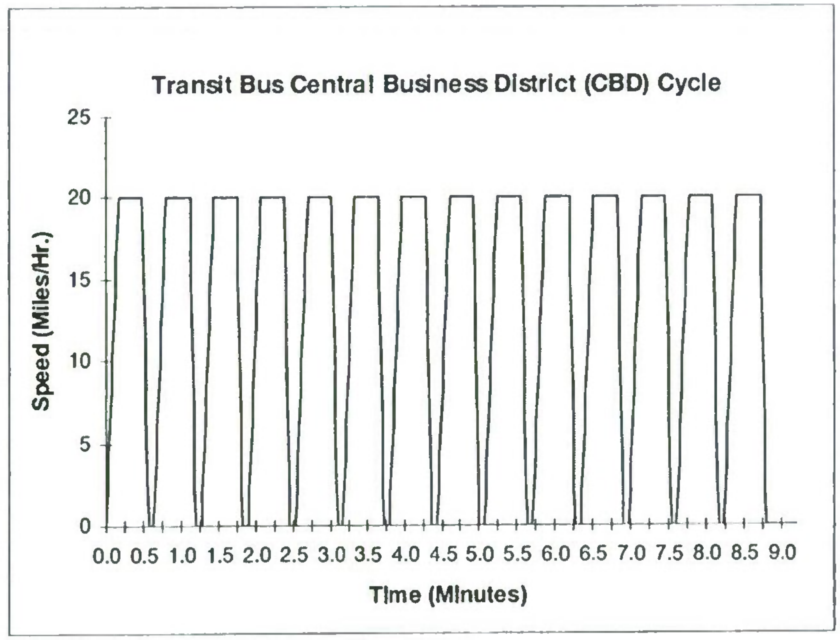
Off-Road 6x6 Military Truck

Dual Use Technology, Flexible Packaging

HEV Fuel Economy

Fuel Savings Depends on Driving Cycle



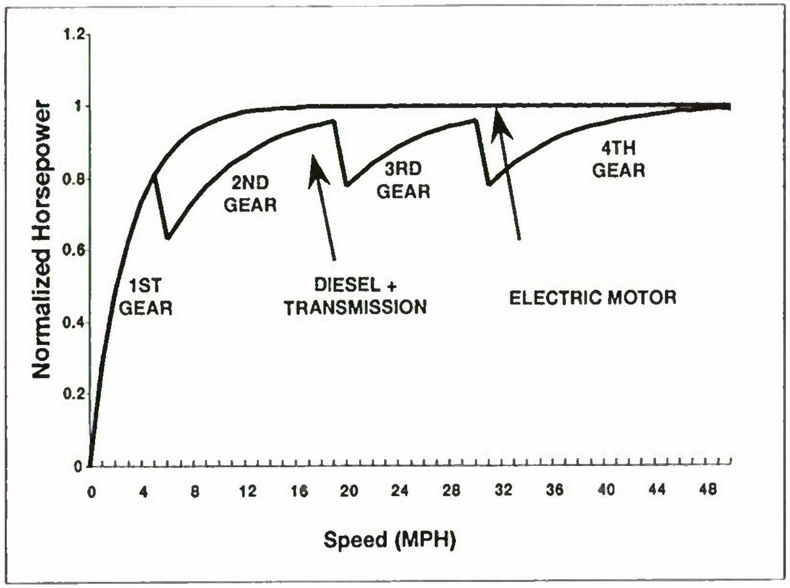


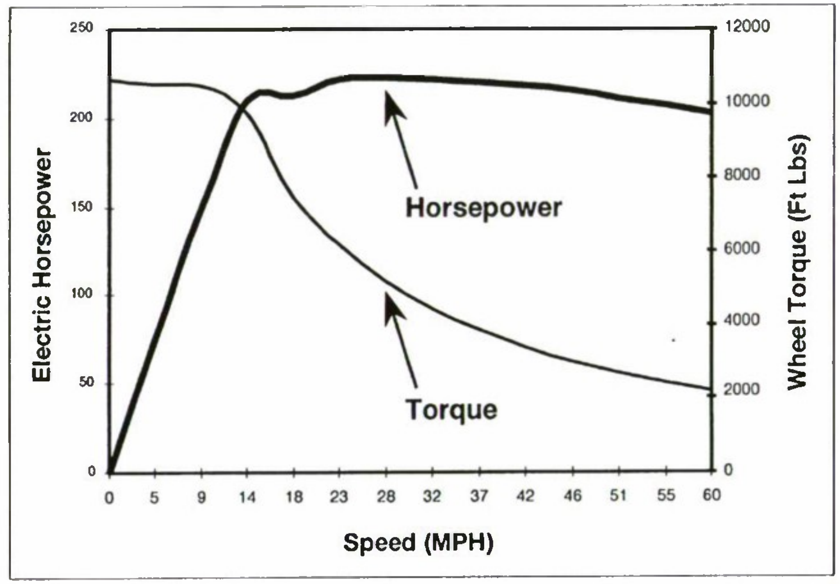
25% Fuel Savings Possible

50% Fuel Savings Possible

- *Fuel Efficiency is Improved through Constant Engine Speed Operation*
- *Efficiency Improvement Increases as Operation Becomes More Cyclic*
- *Regenerative Braking Recovers Braking Energy for Later Use*
- *Operations Analysis for each Vehicle Type will reveal Potential Fuel Savings*
- *Large Efficiency Gains can be made during Low Speed or Still Operation*

HEV Performance Improvement





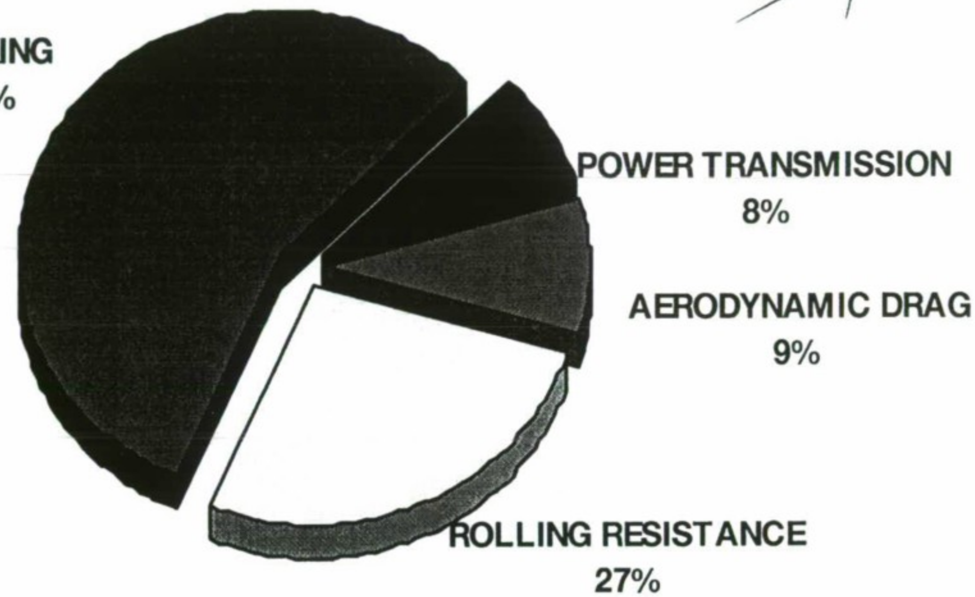
Driving Characteristics

- *Drives like a **"Single Gear"** Automatic Transmission*
- *No clutch pedal, gears or shifting*
- *Drive Train power is delivered smoothly from stand still to top speed*
- *Accelerates from 0 to 60 twice as fast as the comparable conventional drive train vehicle*
- *All driving characteristics are software programmable*

Torque Characteristics

- *Electric drive provides significantly different speed torque characteristics than conventional drive*
- *Full torque at zero speed provides excellent starting characteristics, curb climbing, and grade capability*
- *Low end torque increases acceleration and improves performance in mud, sand*

HEV Regenerative Braking



56% of a standard vehicle's kinetic energy is lost during braking

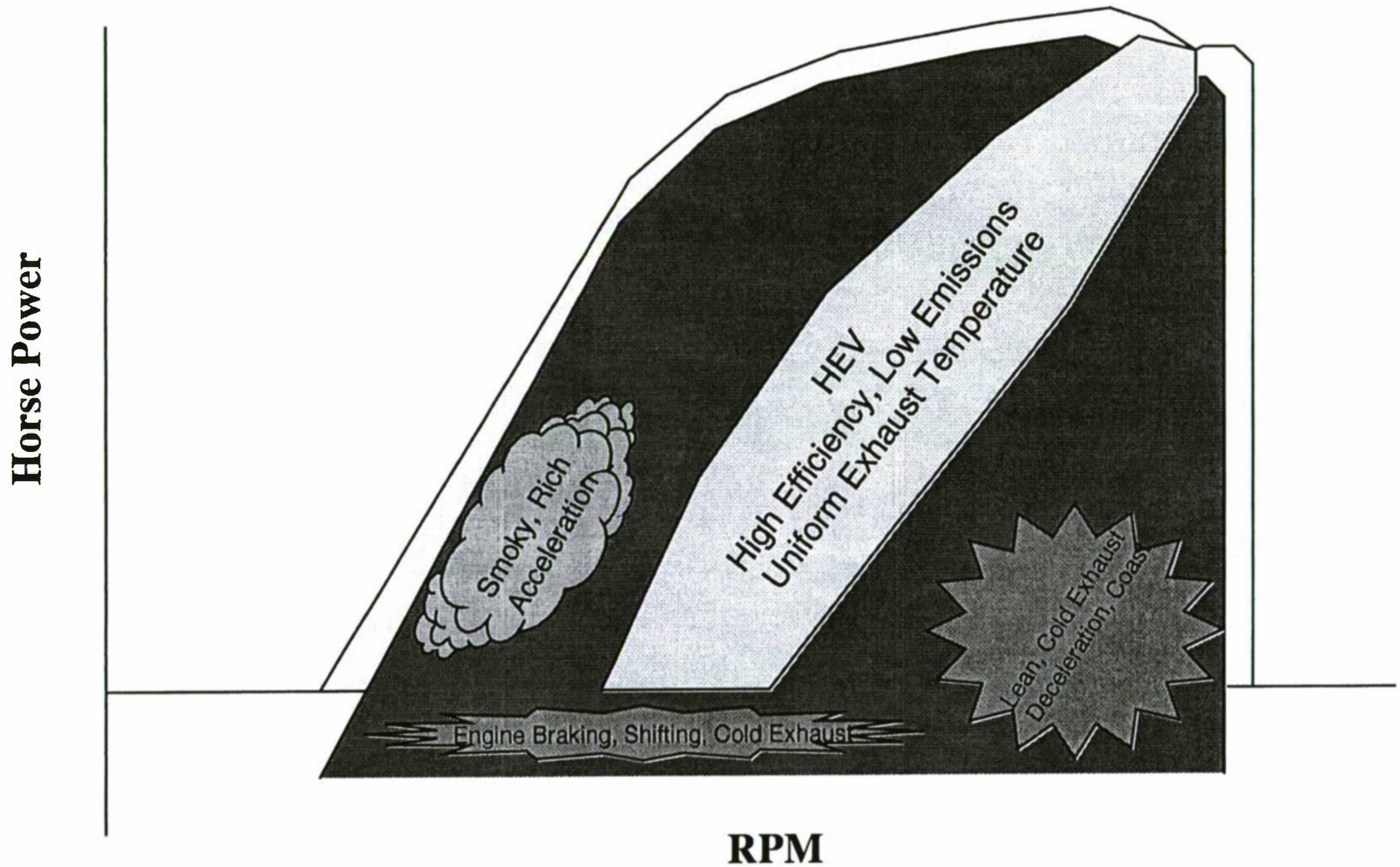
- ***The energy is dissipated as heat in the Service Brakes***
- ***In theory, this energy is recoverable***

With HEV, some of the braking energy is returned to the battery

- ***Electric motor (re)generates and stores braking energy in the batteries***
- ***HEV recovers as much as 50% of the recoverable braking energy***
- ***HEV uses this energy again for acceleration and propulsion***
- ***Consequently, Brake Wear is reduced by about 2/3***

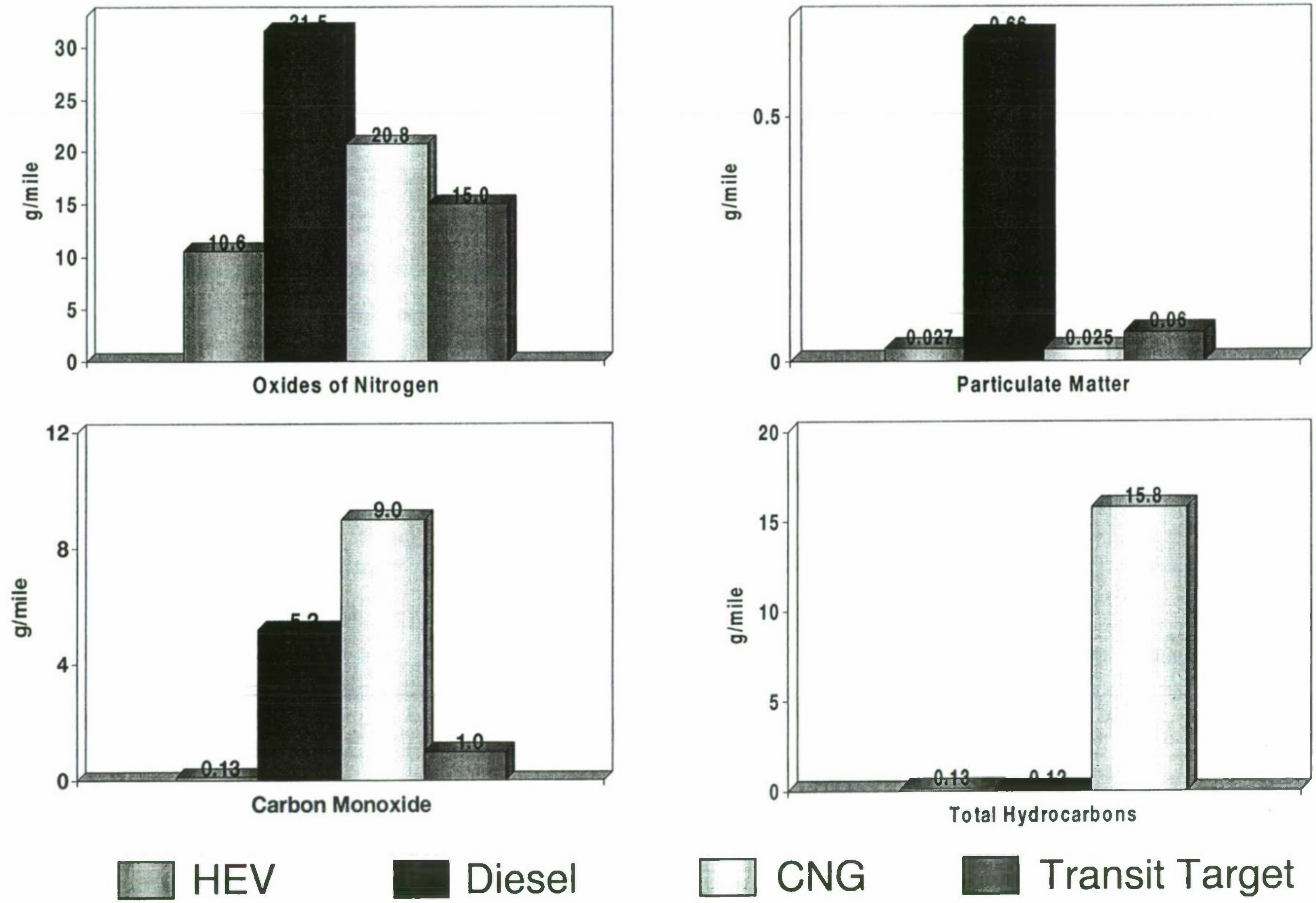
Regenerative Braking Saves Fuel and Brakes!

HybriDrive™ Diesel Engine Operation



Consistent, Predictable Operating Range Saves Fuel and Reduces Emissions!

HybriDrive™ Transit Bus Emissions



Lockheed Martin Control Systems

LMCS HEV Bus Experience

Orion Demonstrator Bus
- Diesel Series Hybrid 40' Transit Bus
- 2 - 125 hp AC Motors with Inverters
- 70 kW Generator
- Slated for upgrade to Generation II

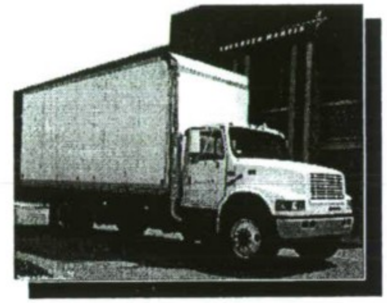
Orion Transit Bus Program
- Diesel Hybrid Electric 40' Transit Bus
- 1 - 250 hp AC Motor with Inverter
- Mechanical Drive Accessories
- 5 of 10 Prototype buses in Revenue Service with New York City MTA

Nova Transit Bus Program
- Diesel Series Hybrid 40' Transit Bus
- 1 - 250 hp AC Motor with Inverter
- All-Electric Accessories
- 5 to be delivered to NYC MTA by 2000

Georgetown Fuel Cell Bus Program
- Based on Transit Bus Propulsion System
- 100 kW Phosphoric Acid Fuel Cell
- Custom Power Electronics
- All-Electric Accessories

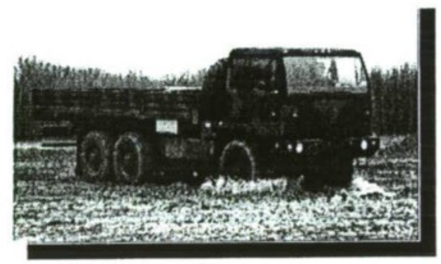
LMCS HEV Truck/Taxi Experience

Medium Truck Program
- Diesel Series Hybrid Class 5 - 7 Trucks
- 1 - 175 hp AC Motor with Inverter
- 4 Prototype Vehicles on the Road



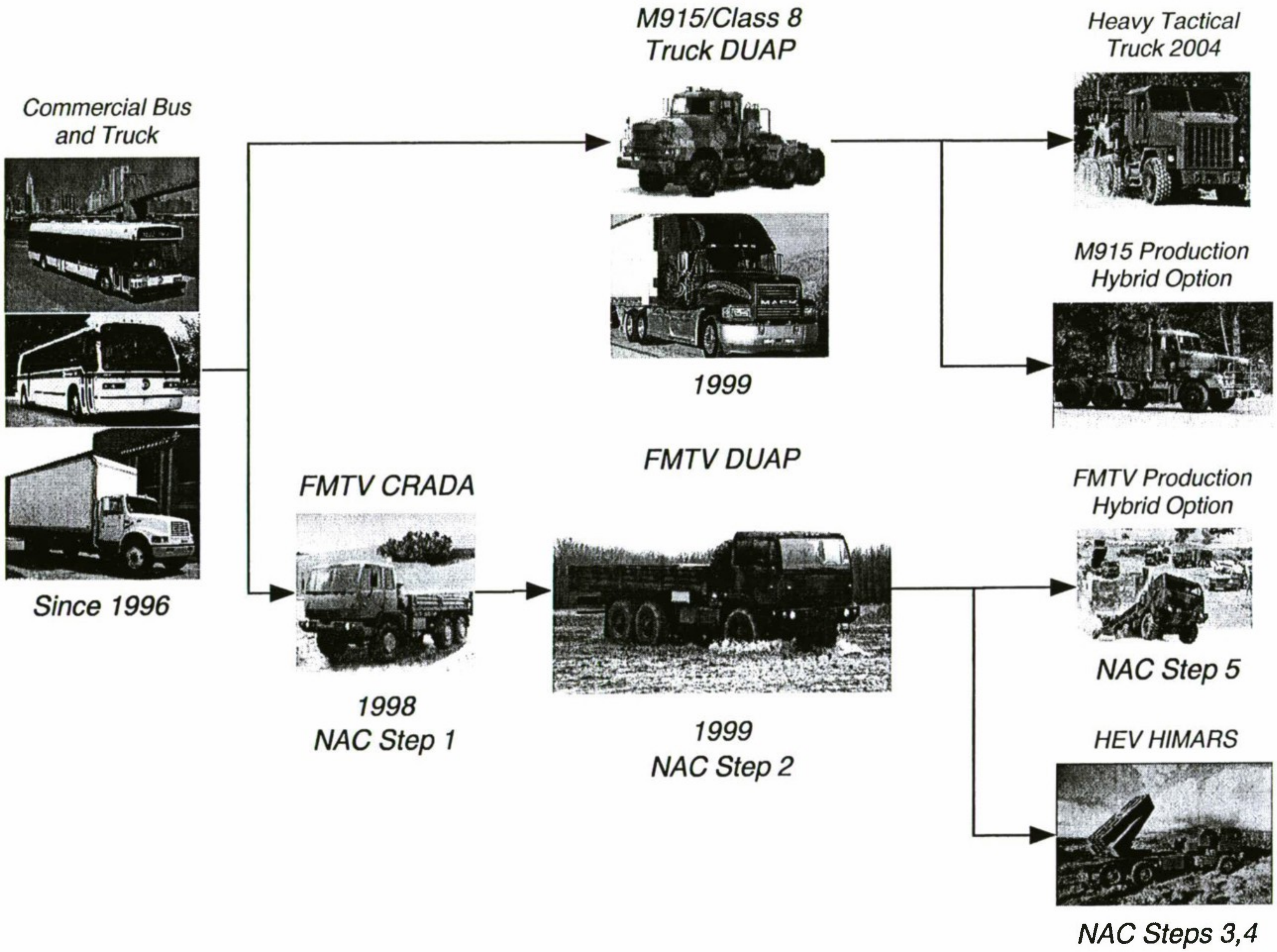
Taxi Program
- Compressed Natural Gas (CNG) Powered American Disabilities Act (ADA) Compliant Series Hybrid Taxi Cab
- 1 - 125 hp AC Motor with Inverter
- All testing complete

FMTV Military Truck Program
- Diesel Series Hybrid 5-ton FMTV
- 2 - 250 hp AC Motors with Inverters
- Slated for Off-Road Testing at Aberdeen Proving Grounds this summer



M915 Line Haul Tractor Program
- Diesel Parallel Hybrid Class 8 Tractor
- 2 - 250 hp AC Motors with Inverters
- 460 hp Diesel Engine with 300 kW Induction Generator
- Program started 4/99

Dual-Use HEV Roadmap



Summary

- *Hybrid Electric Propulsion offers Significant Benefits to Military Vehicles*
- *Commercial Applications are driving the development of Hybrid Electric Propulsion*
- *Dual Use Application Programs are making this technology available to the Army*
- *Fuel Cells integrate well with Hybrid Electric*
- *Hybrid Electric Propulsion will be available to the Army in the Near Term*

HEV - Army After Next Technology Here Today!

Hybrid-Electric Family of Medium Tactical Vehicles Program

Robert Crow III
U.S. Army
Tank & Automotive Research, Development and Engineering Center
National Automotive Center
Technology Advancements Group

Hybrid FMTV Program

- Objectives
- 5 Step Program
- Simulation

Hybrid FMTV Program

Objectives

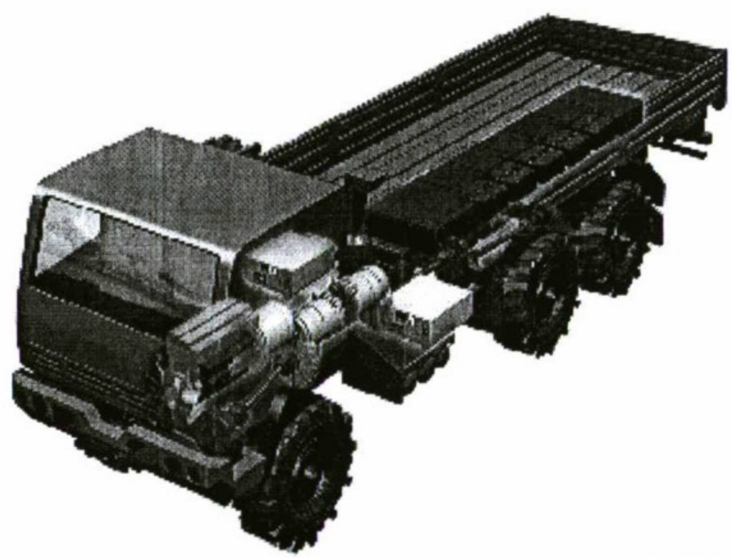
- Improve fuel economy
- Improve mobility & acceleration
- Provide on-board mobile electric power
- Reduce operation and support (O&S) costs
- Introduce new tactical capability (stealth)
- Reduce emissions

Develop a hybrid-electric powertrain that can be introduced into the FMTV fleet as a technology insertion program and/or retrofit.

Hybrid FMTV Program

Step 1

Explore/demonstrate basic technology
- Demonstrator vehicle fabricated
- Ride & drive opportunities held
- Conduct basic performance testing
- Lab evaluation of other HEV battery technology

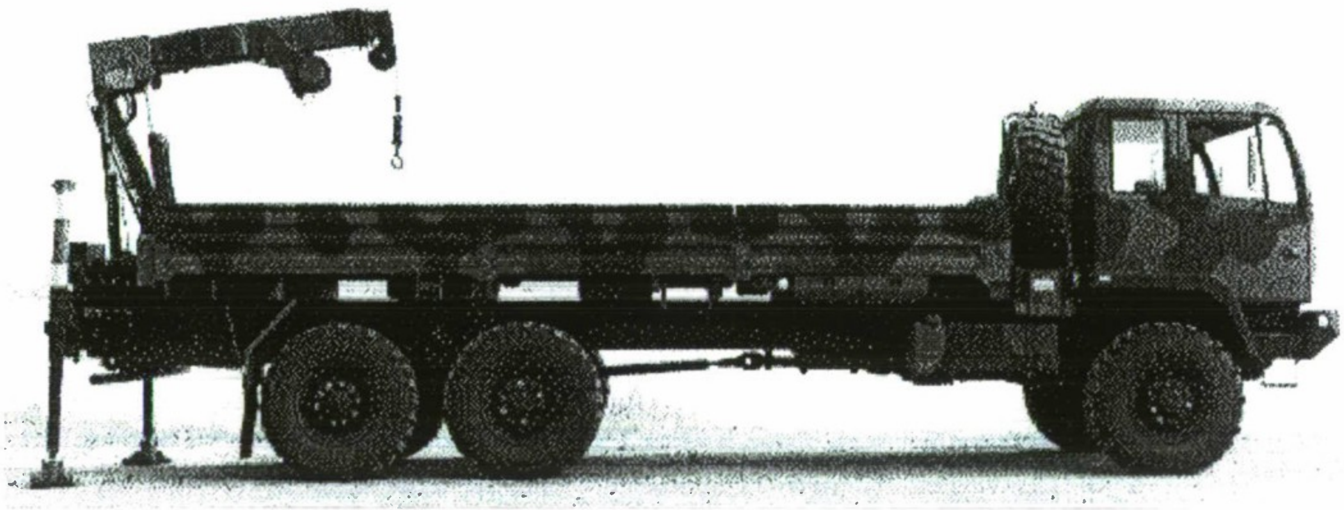


Hybrid FMTV Program

Step 2

HEV system maturation and optimization

- Integrate 2nd generation hybrid hardware
- Militarize as practicable
- Expanded testing at Aberdeen Proving Grounds, MD



Hybrid FMTV Program

Step 3

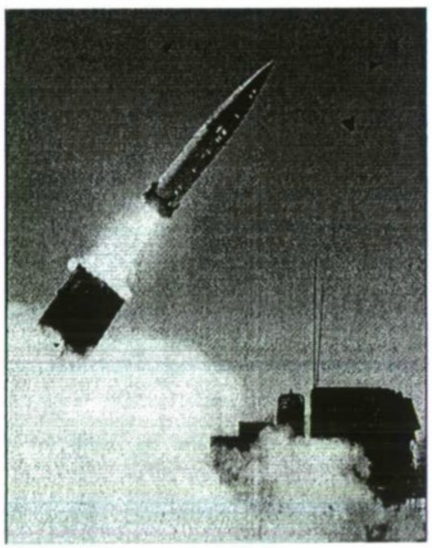
Hybrid High Mobility Artillery Rocket System (HIMARS) study

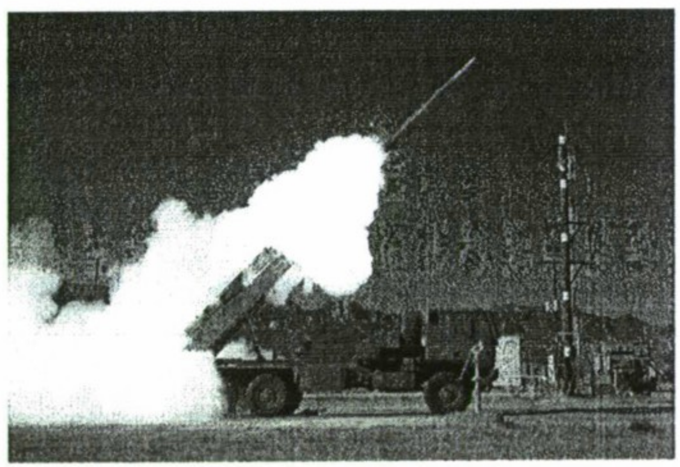
- Must be C-130 transportable (29,000 lbs - loaded)
- Identify O&S cost reduction opportunities
- Convert launcher hydraulics to electric motors?

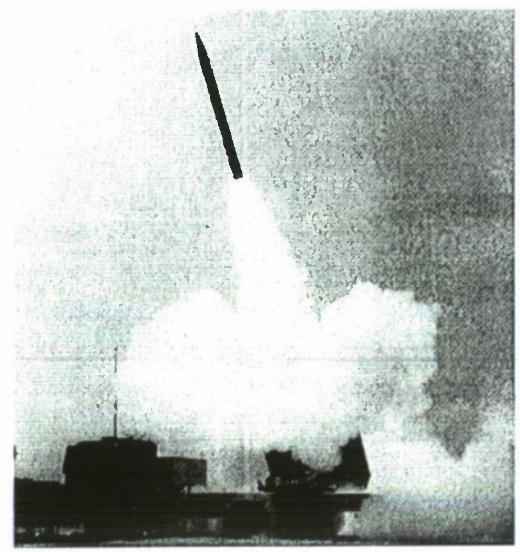
Hybrid FMTV Program

Step 4

Fabricate Hybrid HIMARS Prototype
- Integrate HIMARS Launcher
- Integrate HIMARS Cab
- Reduce system weight
- Formal APG/user testing



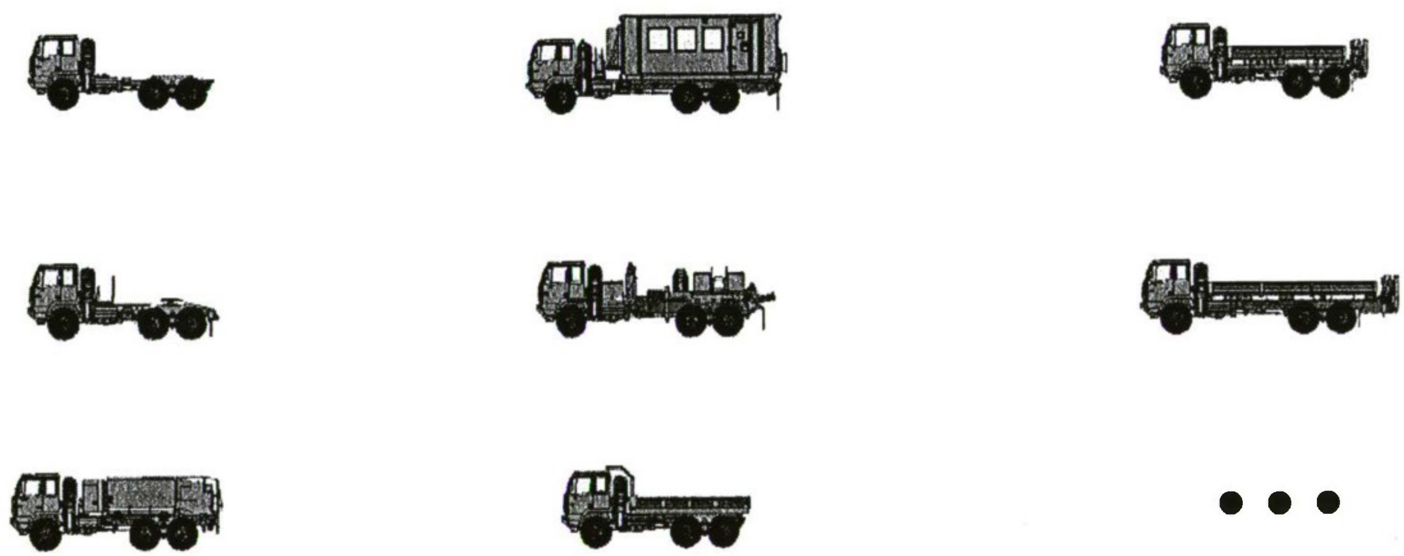




Hybrid FMTV Program

Step 5

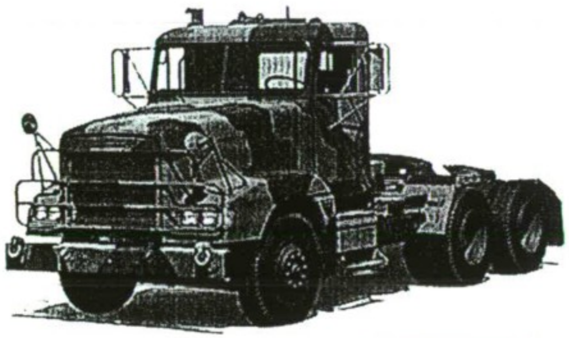
Develop production ready universal HEV FMTV powertrain
- Simulate all FMTV variants
- Build select prototypes
- Formal APG testing



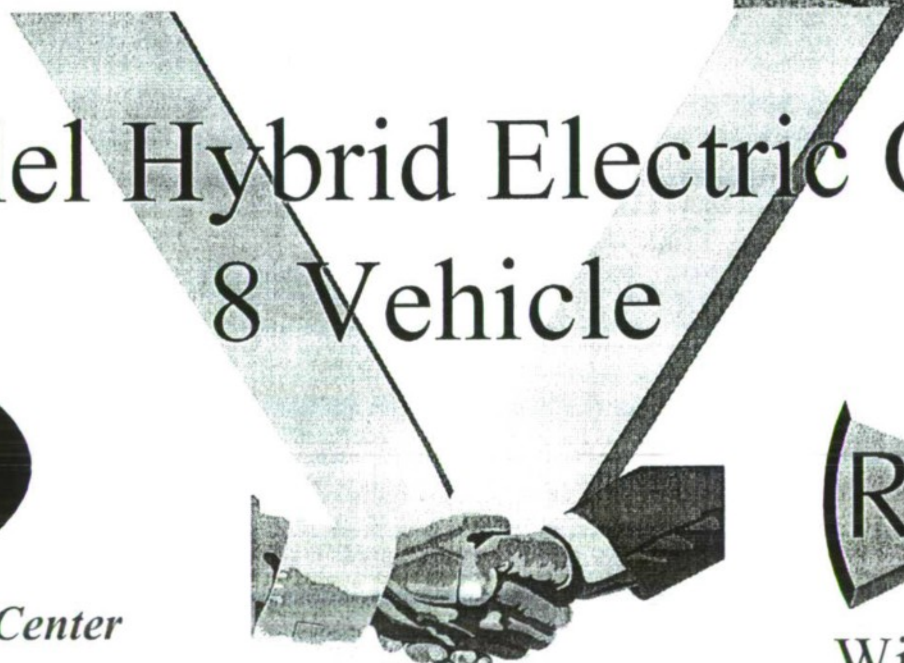
Hybrid FMTV Program

Simulation Throughout the Life Cycle Plans
(SIM-TLC)

- Component space claims
- Dynamic modeling of new components/mounts
- Dynamic modeling of vehicles on virtual test courses
- Propulsion system performance optimization
- O&S cost calculations/monitoring
- Maintenance issues from users (using CAIV system)
- Manufacturing/producability issues
- Input/feedback from tactical ‘war game’ simulations



Parallel Hybrid Electric Class 8 Vehicle



NAC

National Automotive Center

Harold Sanborn

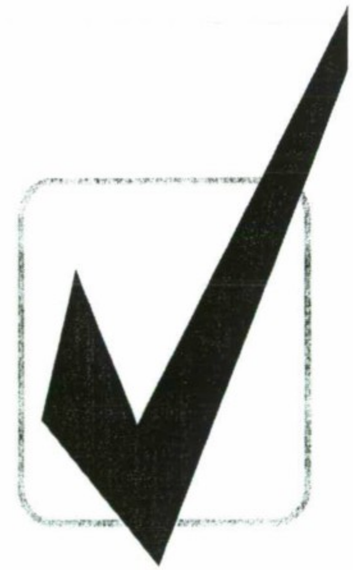
RADIAN

William Haris

Demonstration for the 21st Century Truck

- *To significantly increase the fuel economy of light, medium, and heavy trucks while at the same time improving vehicle performance and reducing carbon dioxide emissions.*
- *Heavy Trucks: Demonstrate improved fuel economy > 10 MPG by 2005 > 13 MPG by 2010*

NAC/Radian Goals



- Increase Performance
- Increase Fuel Economy
- Decrease Emissions
- Maintain/improve Life Cycle Cost
- Demonstrate Oil Reutilization
- Pass the lessons learned to Program Manager and Commercial Partners
- Add goals as they make sense

Vehicle Technologies Conference

OBJECTIVE

- Design, fabricate, demonstrate and evaluate a parallel hybrid drive system in a Class 8 vehicle comparing against the performance requirements/TEMP of the M915A3 line haul truck.
- Demonstrate the parallel hybrid drive train achievements toward:
  - enhancement in fuel economy,
  - recovery of braking energy,
  - reduction of pollutant emissions,
  - verify performance: acceleration, grade/speed ratio & traction
  - verify oil reutilization impact on performance.

TECHNICAL CHALLENGES

- Volume and weight of the subsystems and components,
- Cost (manufacturing vs life cycle)
- Cooling of the power electronics.

APPROACH

- Compare candidate demo against performance requirements of the M915A2/3.
- Generate and evaluate configurations for converting a conventional Class 8 line haul truck chassis into a parallel hybrid configuration. Include "regenerative braking" system.
- Perform the physical modifications to the Class 8 truck.
- Conduct baseline tests @ Aberdeen Proving Ground.
- Apply oil reutilization technology to the modified platform & verify impact.
- Add best value technology improvements

TASK	CY	CY+1	CY+2
COMPONENT SELECTION			
INTEGRATION DESIGN			
HYBRID DRIVE MODIFICATION			
BASELINE TEST			
OIL REUTILIZATION INTEGRATION	$		
COMPLETE CONTRACTOR TESTING			
VEHICLE & REPORT DELIVERED			
FUNDING	$2.1M	$815K	$469K

MAJOR MILESTONES

•Identification of primary subsystems/components	2Q99
•Selection of integration design	4Q99
•Hybrid drive modification completed	2Q00
•Baseline test completed	3Q00
•Oil reutilization technology integrated	4Q00
•Contractor testing finished	2Q01
•Vehicle and test report delivered to TARDEC	3Q01

CONTRIBUTION TO TECHNICAL OBJECTIVES

- enhancement in fuel economy,
- recovery of braking energy,
- reduction of pollutant emissions,
- performance improvements in acceleration, traction, and verify oil reutilization impact on performance.

NAC

RADIAN

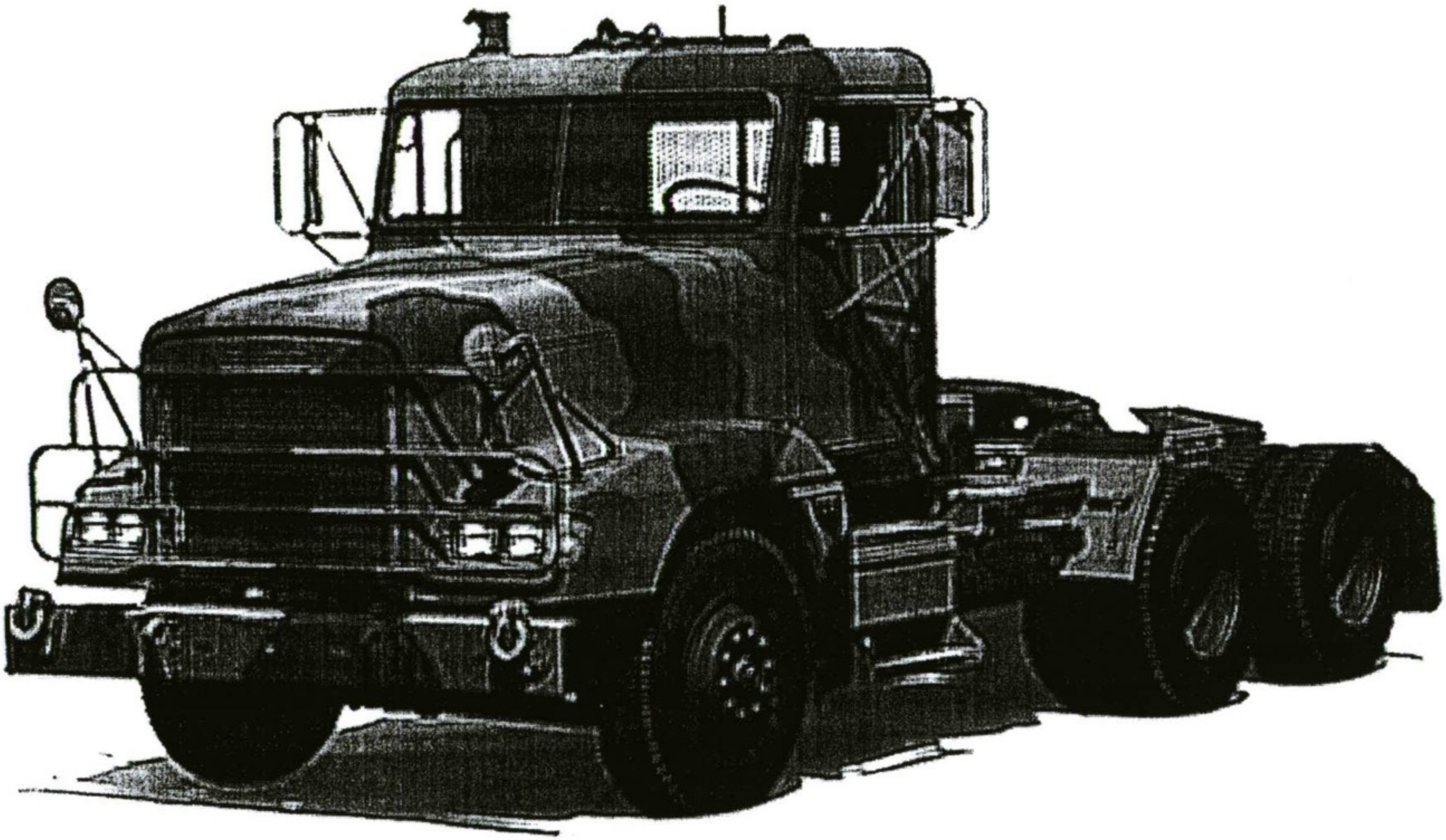
DUST

A Partnership Leveraging the best of all parties.

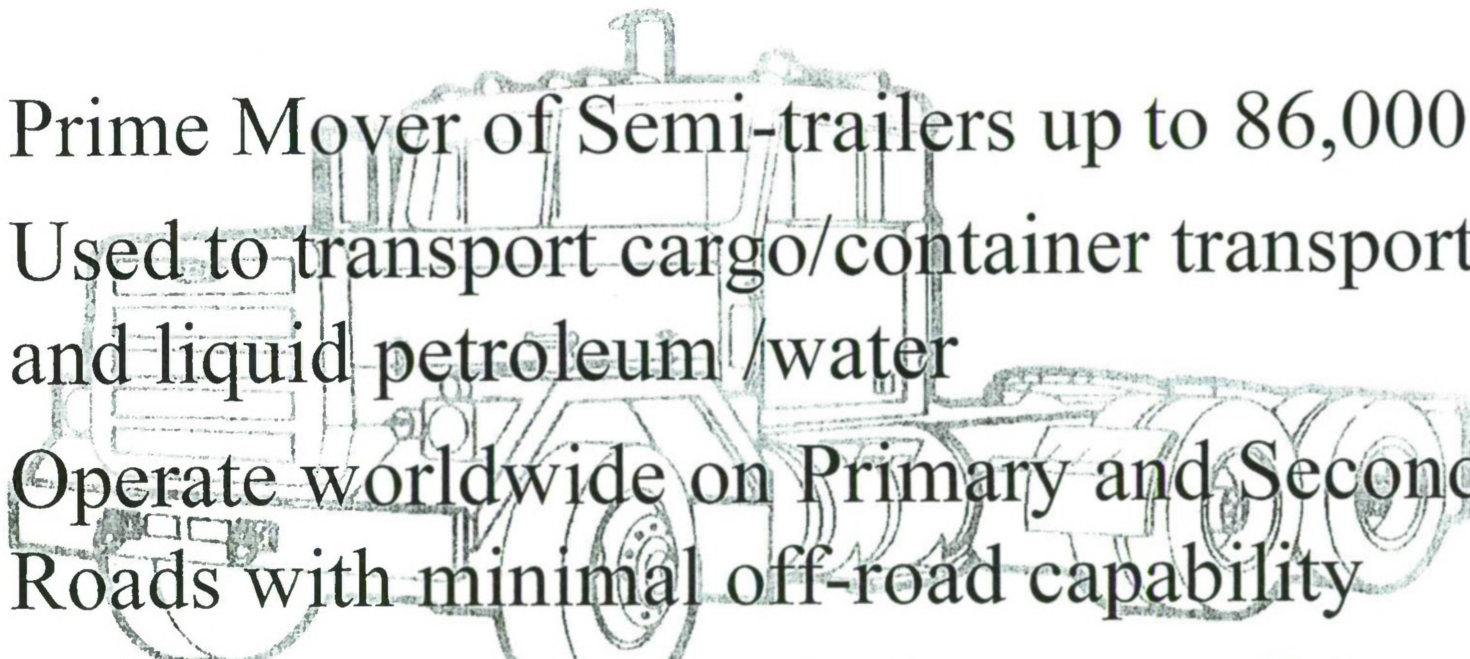
LOCKHEED MARTIN

Mack

M915-A3

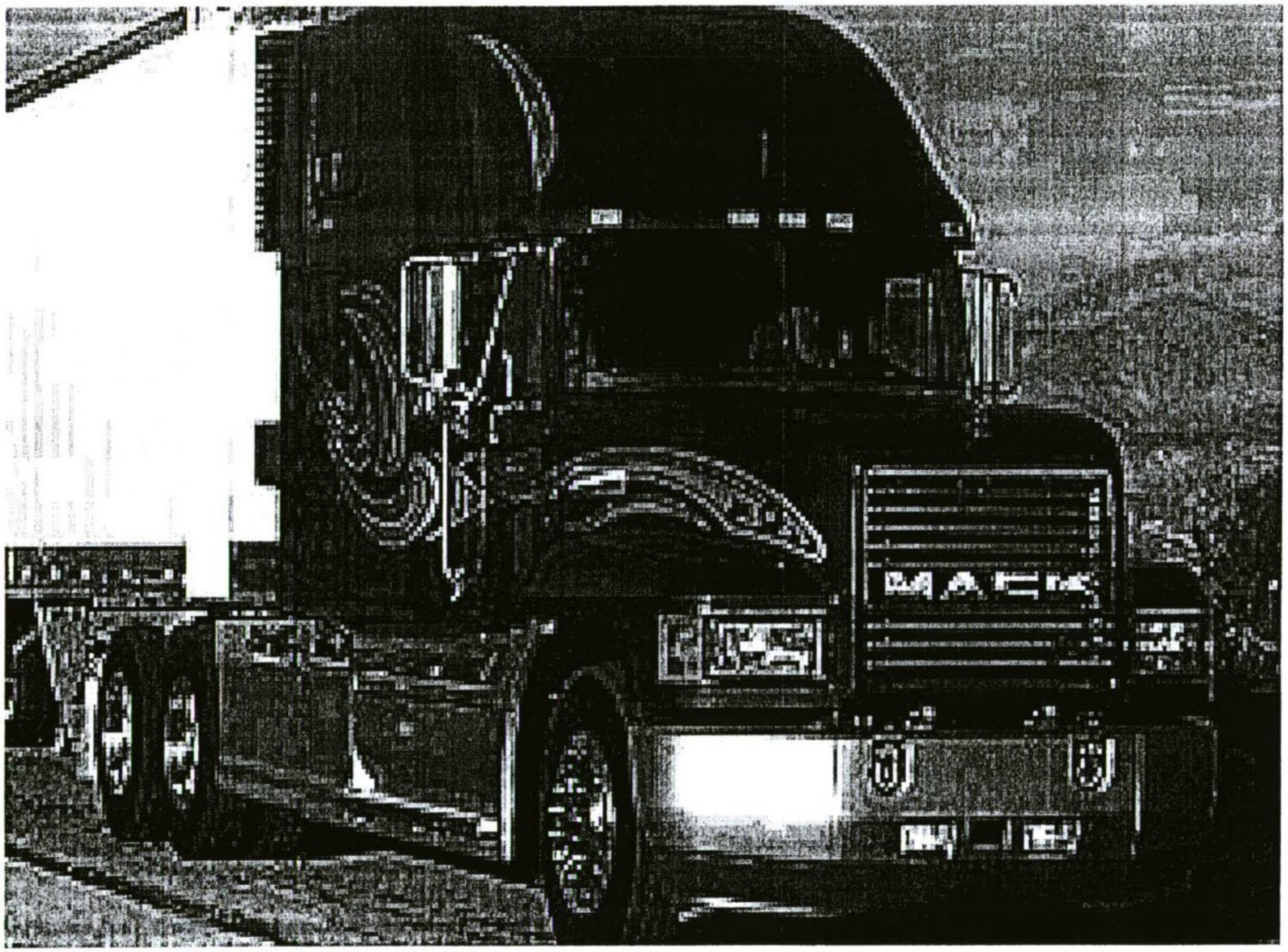


M915-A3 Requirements



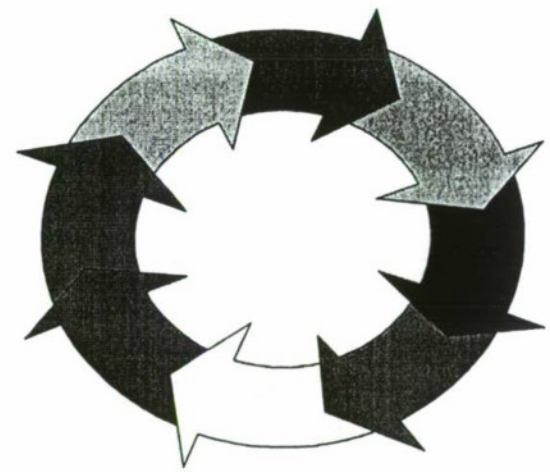
- Prime Mover of Semi-trailers up to 86,000 LB.
- Used to transport cargo/container transporter and liquid petroleum /water
- Operate worldwide on Primary and Secondary Roads with minimal off-road capability
- Used in all weather and climate conditions

Mack CL713

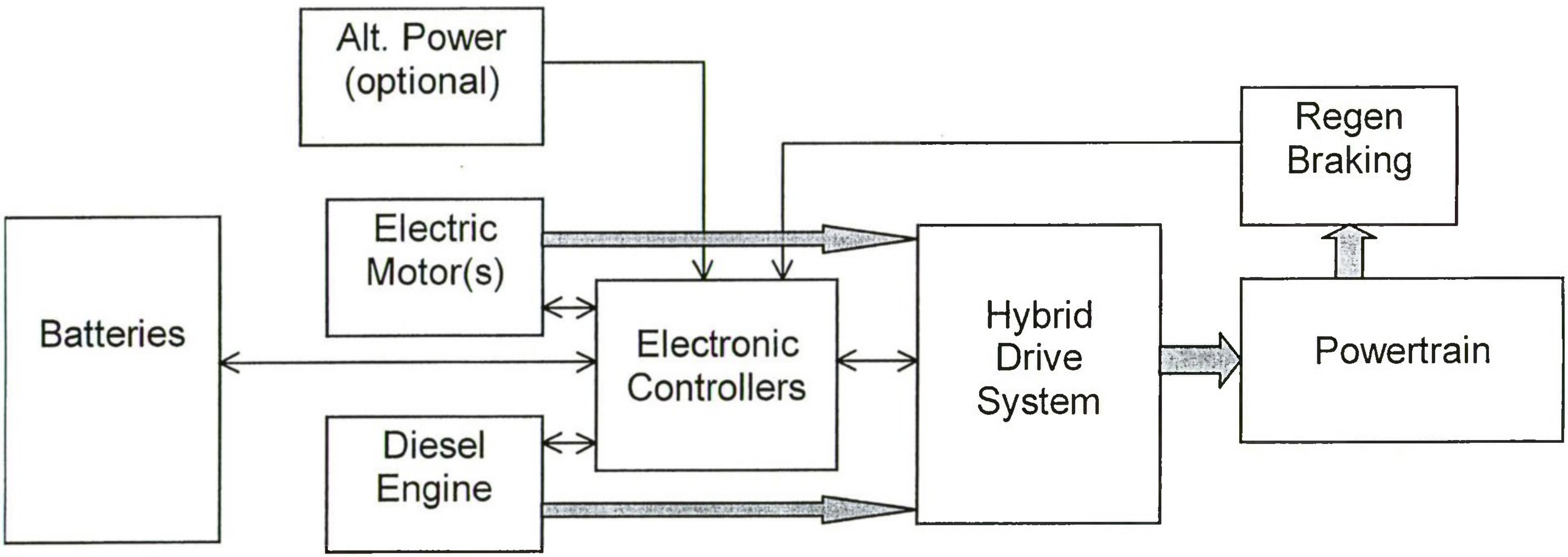


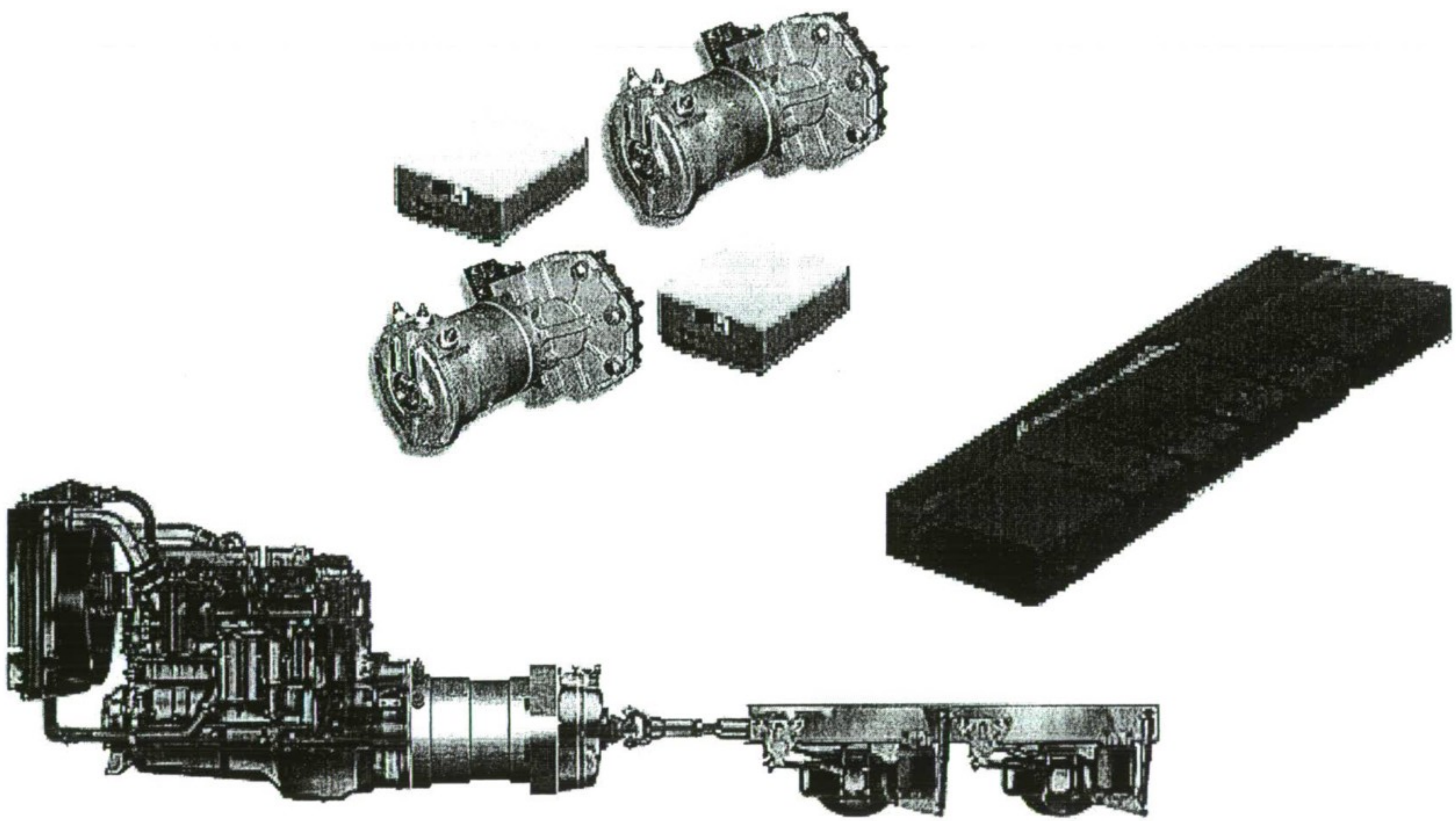
Vehicle Components

- Battery Pack
- Electric Controllers
- Electric Motors
- Hybrid Drive System
- Diesel Engine
- Electric Generator



HEV Architecture





Project Goals

- Compare Performance to M915-A3
- Reduction in pollutant emissions
- Recover Braking Energy
- Increase fuel efficiency
- Implement used oil reutilization

Challenges/Issues

- Drive train placement/configuration Vehicle
- Mechanical Coupling System between power sources
- Weight/Performance Trade-off
- Energy Storage Device(s)

Potential Additions

- Energy Storage (NiMH, Li, etc.)
- Alt. Power (fuel cell, solar panel, etc.)
- Advanced Battery Management
- Non-water based engine coolant solution
- Thermal Viewer
- Collision Warning

Key Players

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    email: sanbornh@tacom.army.mil
- LMCS
  - Steve Cortese
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    email: stephen.cortese@lmco.com
  - Jody Lanfranchi
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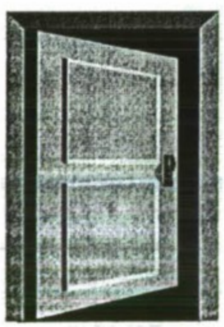
    email: jody.lanfranchi@lmco.com



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- Mack Trucks
  - Dan Wickline
  - phone: (610)709-2489

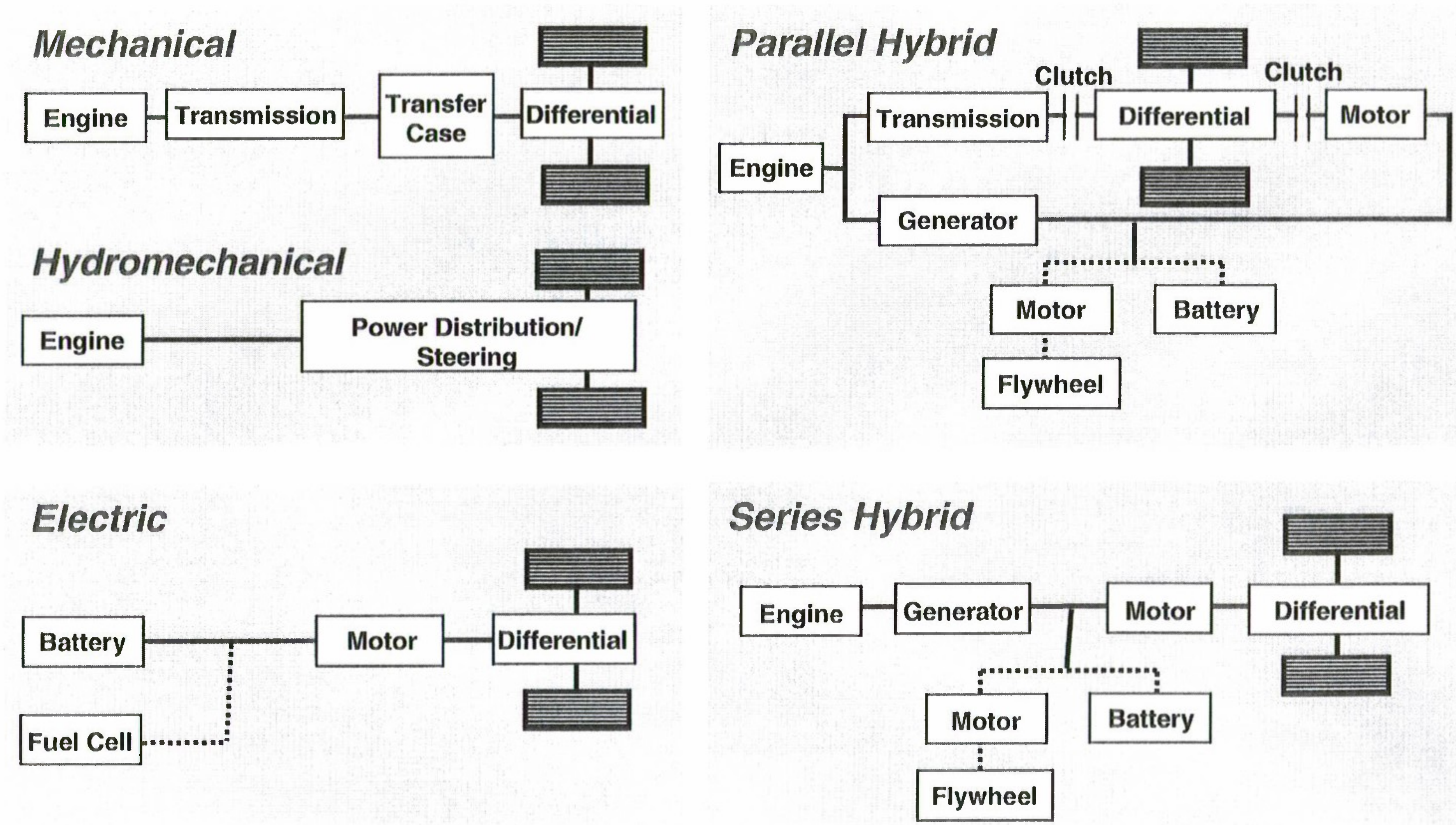
Combat Hybrid Power Systems

Marilyn Freeman

Program Manager
Tactical Technology Office

Defense Advanced Research Projects Agency

Overview: Drivetrain Configurations



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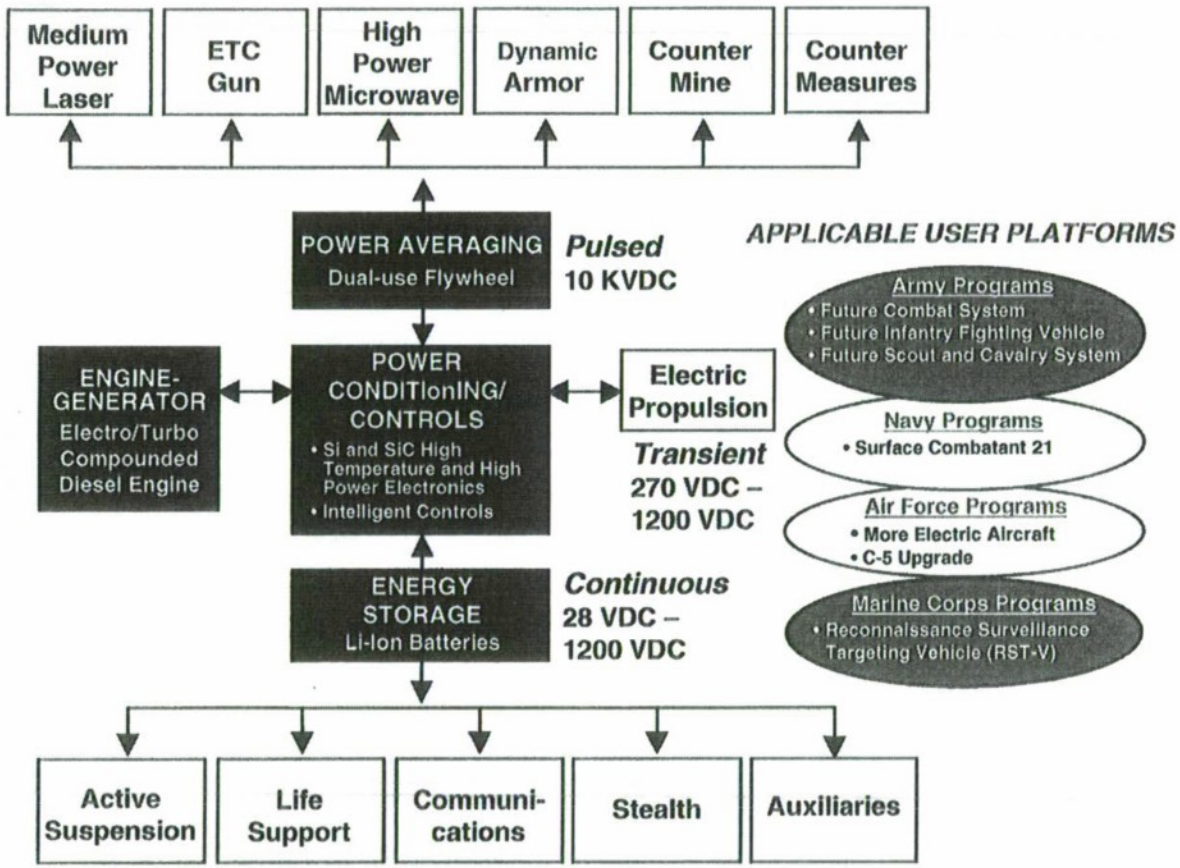
Concept Chart

Combat Hybrid Power Systems(CHPS)



Objectives

- Develop and demonstrate hybrid electric power system for 15 ton class combat vehicles in a systems integration laboratory (SIL)
- Develop validated virtual prototypes for all weight classes of Future Combat Vehicles
- Develop and demonstrate high pay-off, enabling power system component technologies

CHPS: an essential step toward demonstrating that lightweight future ground combat vehicles capable of improved mobility, survivability and lethality are feasible using new design paradigm that emphasizes power component integration and intelligent power management strategies

CHPS
Technical Approach and Challenges

Management Strategy: Two Contractor Teams + Government Advisors = 10 IPTs

- SAIC Team (SAIC, UDLP, Maxwell/PI, CEM and SatCon)
- Northrop Grumman Team (NG MASD, NG ESSD, NG STC and SAFT)
- Government/SETA Advisors - DARPA, Army, Navy, SPC, MAPC and IAT-UT

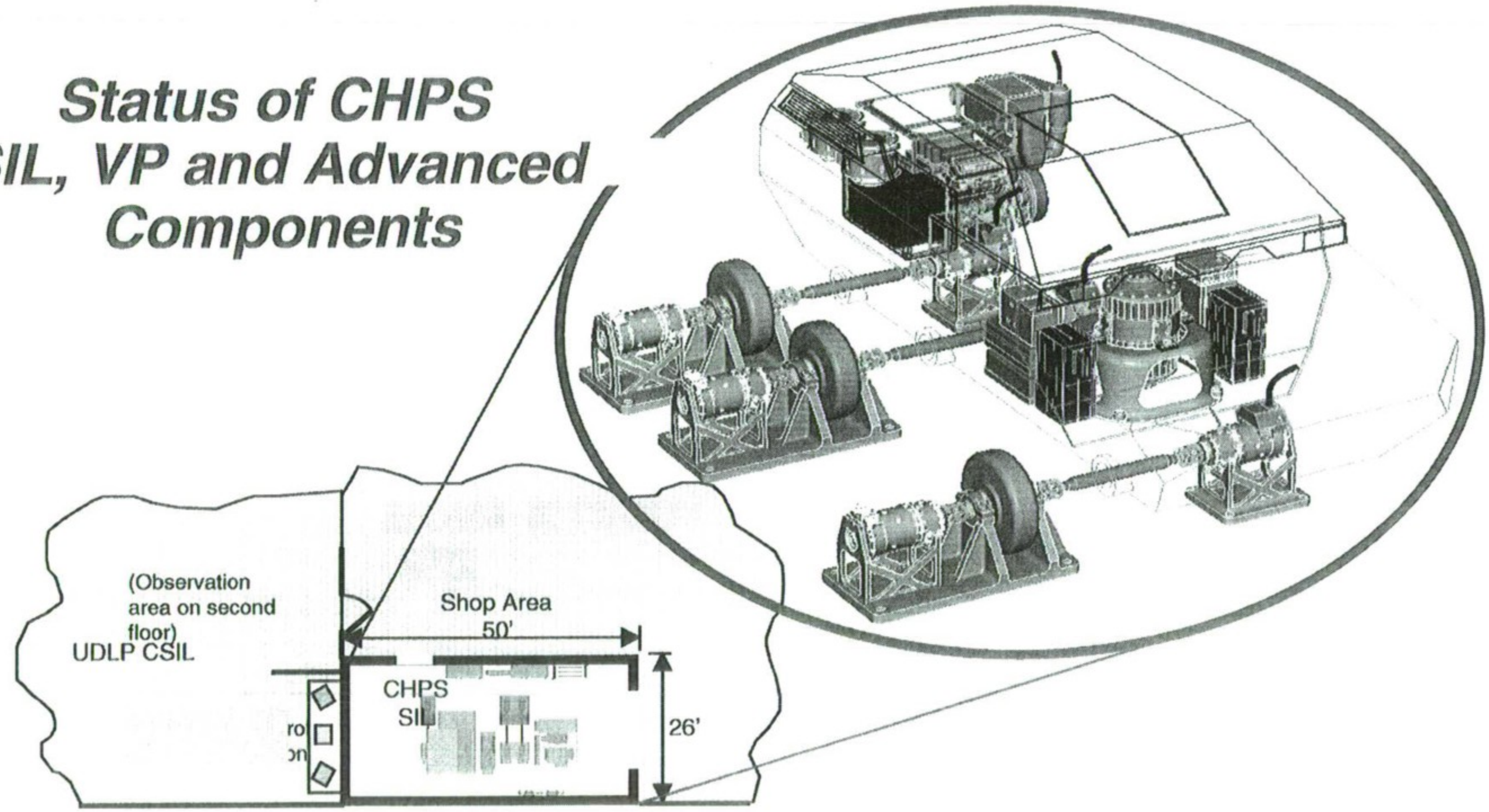
Challenges: Develop affordable, efficient, high-power electrical system architectures and components to generate power, store energy, condition power, and distribute both 100's of kilowatts continuous and multi-gigawatts pulsed power to subsystem loads.

Tasks: Develop system integration laboratory, critical technologies and virtual prototype to evaluate power architecture performance, as well as to explore future combat vehicle concepts for various Army/Marine Corps missions.

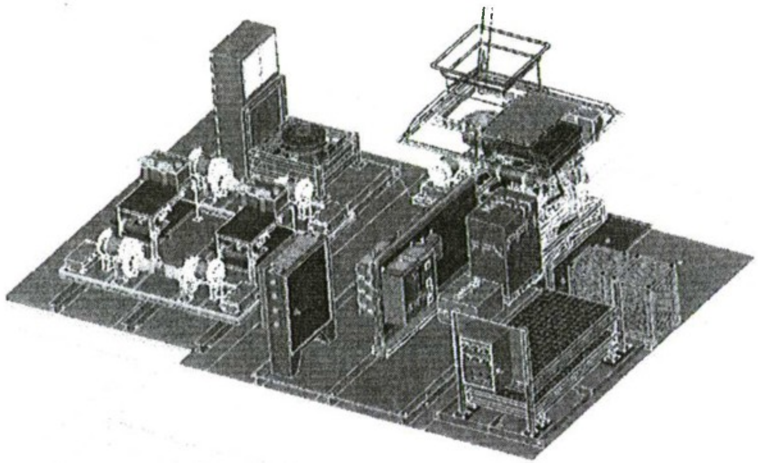
Enabling Technologies	State of the Art	Goal
Prime Power	0.7 kW/kg, 20% effective thermal efficiency	0.7 kW/kg, > 40% effective thermal efficiency
Energy Storage	300 W/kg, 80 W-hr/kg	1250 W/kg, 120 W-hr/kg
Pulsed Power	1.1 MW/kg, 0.8 W-hr/kg	2.5 MW/kg, 1.9 W-hr/kg
High Temp/Power Switches	1200 V, 600 A, 140°C, 20 kHz (Device)	1500 V, 1000 A, 300°C, 50+ kHz (Device)

Accomplishments

Status of CHPS SIL, VP and Advanced Components



System Integration Lab (SIL)



Purpose/Objective

- Integrate CHPS components and support hardware into functioning laboratory
- Conduct testing and evaluation in support of program objectives
- Integrate critical advanced component technologies as they become available

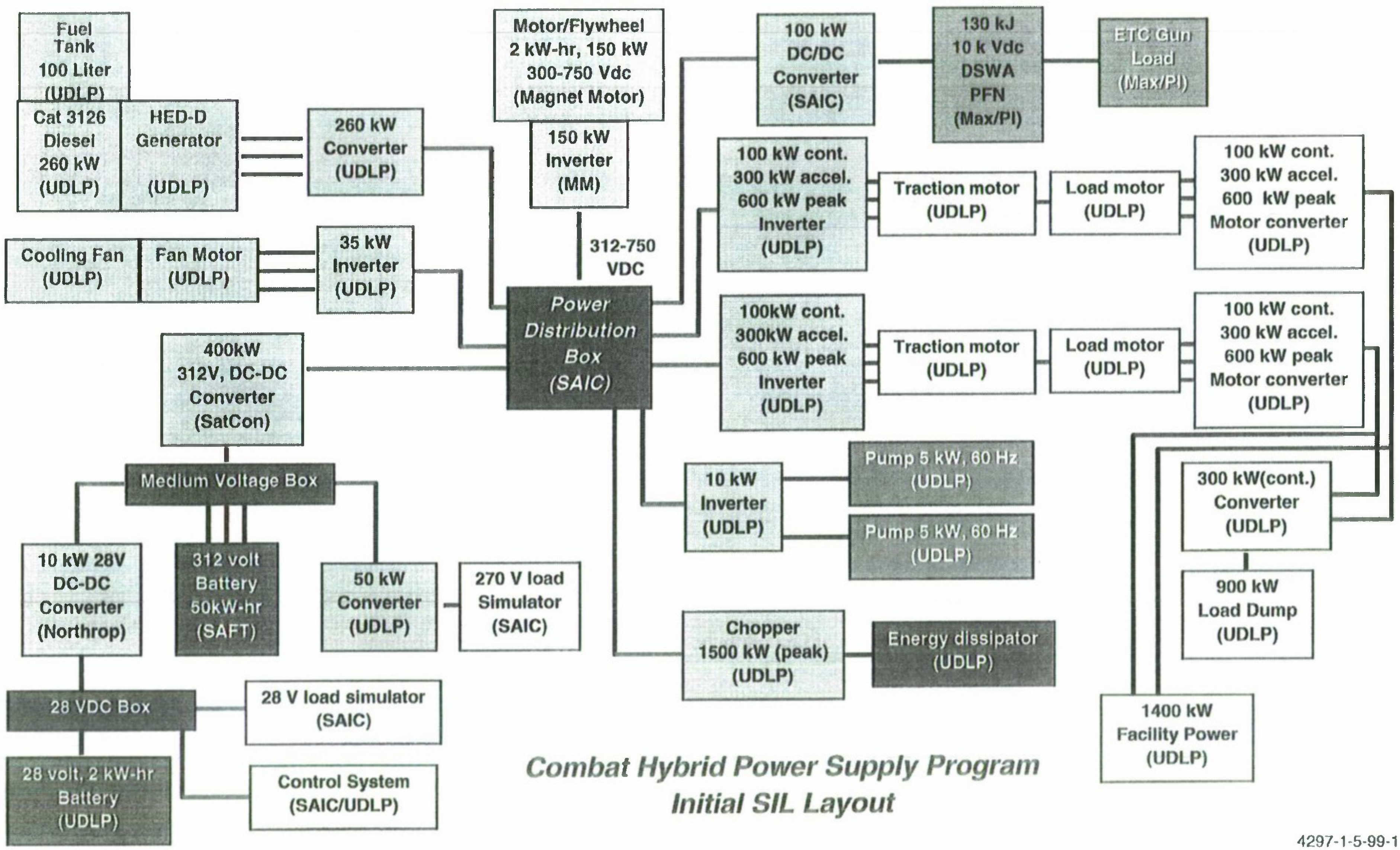
Accomplishments

- Building is complete
- Completed Interface Control Document
- Generated Test Plan (hardware acceptance and Initial baseline performance levels)
- Completed top and second level cabling diagram; third level in-process
- Received and installed hardware

Issues

- Difficult to maintain rigid schedule timeline: large quantity of unique hardware and critical technology components must be installed, tested for proper operation, integrated into a working system and exercised as a safe system to achieve meaningful results
- No show stoppers

Initial SIL Configuration



Combat Hybrid Power Supply Program
Initial SIL Layout

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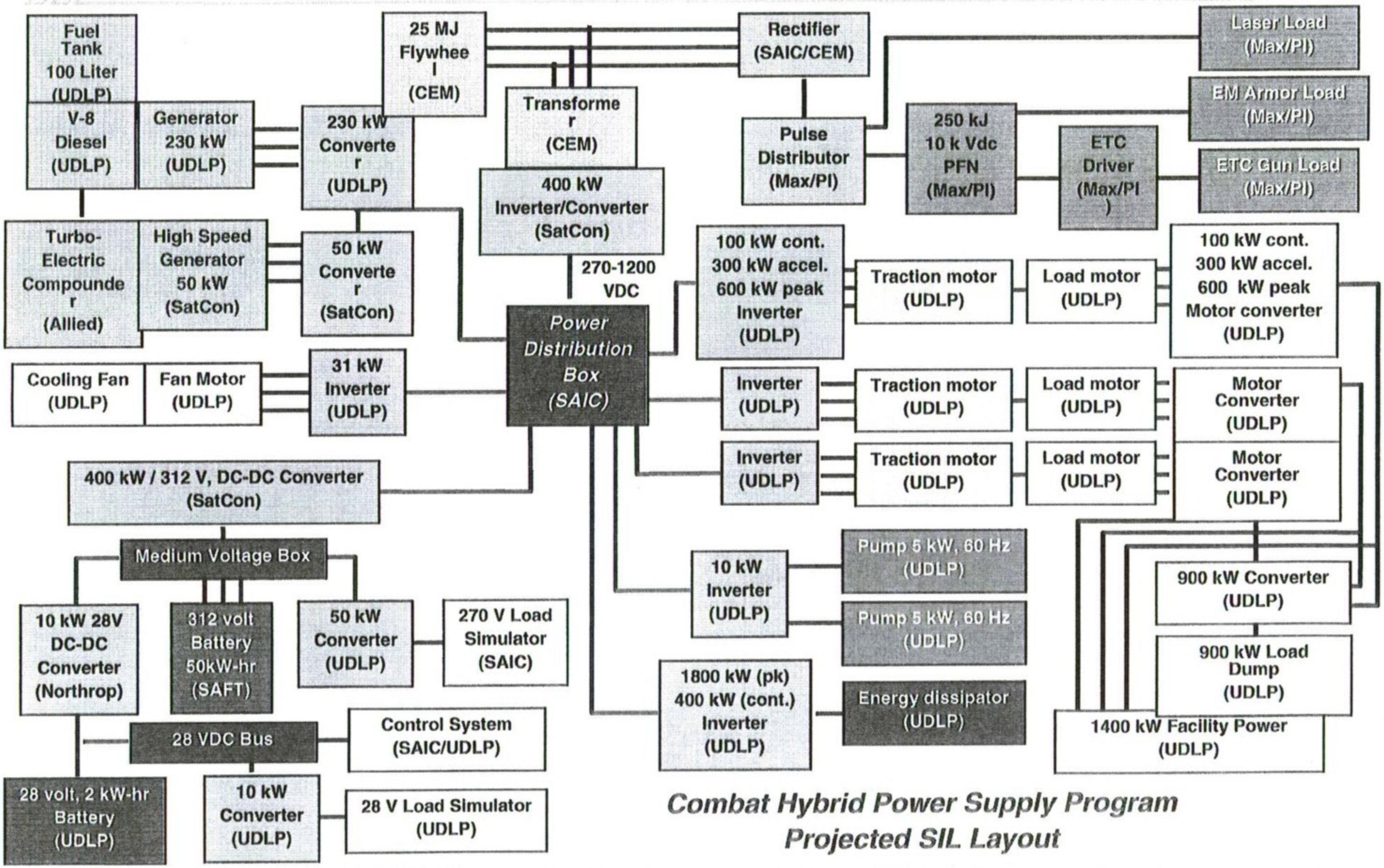
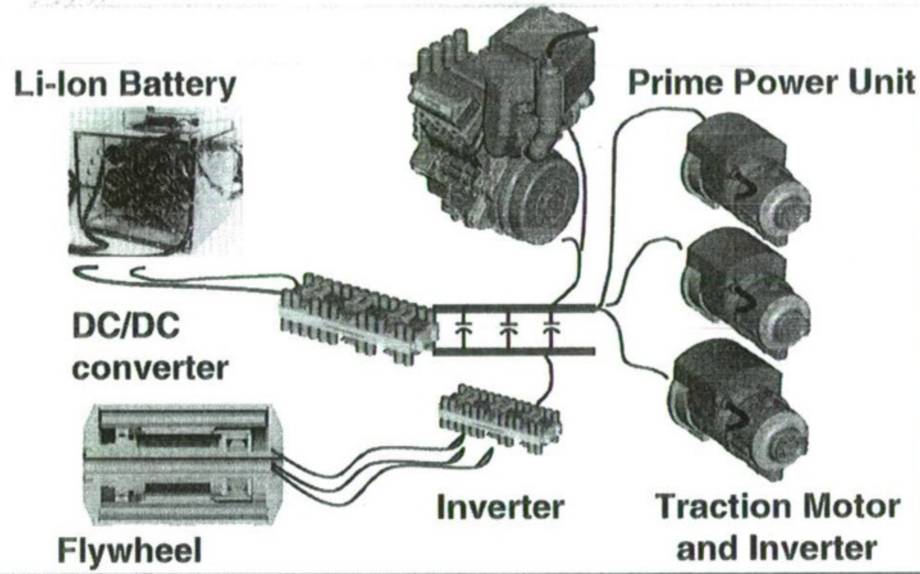
Projected SIL Configuration



Combat Hybrid Power Supply Program
Projected SIL Layout

Power Distribution and Conversion



Purpose/Objective

- Design and implement main power distribution system bus suitable for future combat systems
- Develop stable power distribution system while optimizing volumetric efficiency

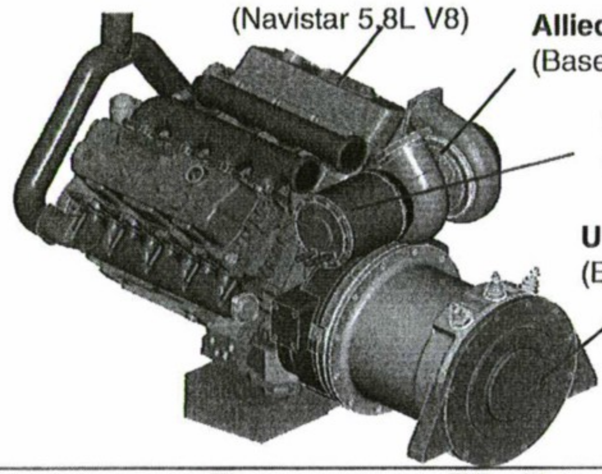
Accomplishments

- Assembled traction-motor converters
- Completed power distribution and battery interface box
- Designed and procured battery DC/DC and generator for turboelectric compounder

Issues

- None at this time
- No show stoppers anticipated

HSDI Diesel with Electric Turbocompounding



Purpose/Objective

- Develop high power-density prime-power unit using high-speed direct-injection (HSDI) diesel with electric turbocompounding
- Develop integrated turbogenerator
- Integrate turbogenerator with an HSDI Diesel
- Demonstrate fuel economy gains and lower signatures in SIL

Accomplishments

- Conducted Critical Design Review; simulations show 6-14% improvement in fuel economy over conventional HSDI diesels
- Finalized turbomachinery & high-speed generator design; performance tests underway
- Tested generator end ring & spun test rotor to 112,500 rpm
- Initiated diesel motor testing at Navistar and detailing of CHPS hardware

Issues

- None

Flywheel Energy Storage

Purpose/Objective

Demonstrate dual-mode hybrid combat vehicle flywheel energy storage system compatible with hybrid electric power systems of combat vehicles

25MJ Energy Storage
- 5MW/700kW Pulse/Mobility Modes
- 350kW average power

Accomplishments

- Demonstrated Permanent Magnet (PM) assembly process with surrogate magnets, at full elastomer compression
- Conducted cycle testing of PM cartridge
- Completed round of hydroburst fatigue tests on composite rings
- Completed mock-up of stator winding
- Completed Preliminary Design Review

Issues

- No technical issues
- Safe operation

  In conjunction with Electric Vehicle Program, developing assurance of flywheel safety, establishing lifetime design margins and/or containment requirements

Lithium Ion Battery

Purpose/Objective

- Provide initial NiCd battery energy storage system for SIL
- Develop electrical model of Li-Ion technologies: energy, power & dual mode
- Demonstrate functionality of Li-Ion energy storage as an integral part of SIL
- Select appropriate battery design SIL
- Deliver: Li-Ion battery to SIL (goal:30KWhr)

Accomplishments

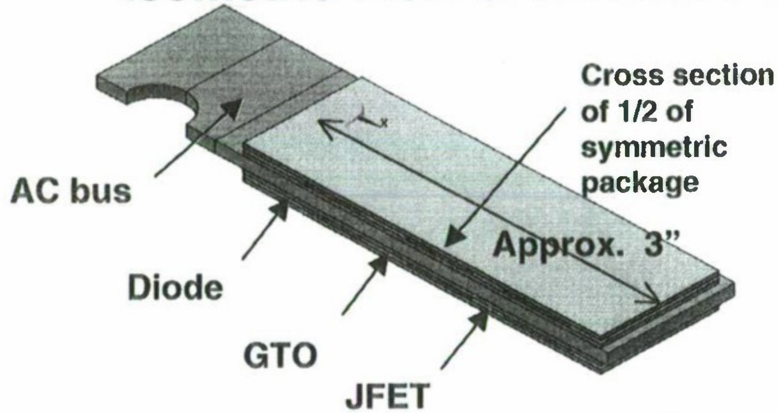
- Development of Dual Mode cell on schedule
- Testing of High Power & High Energy cells
- Developed electrical models of High Power & High Energy cells
- Developed electrical model of Dual Mode cells
- Demonstrated battery performance in excess of program goals at cell level

Issues

- None
- Cell performance exceeds available test equipment

SiC Flywheel Inverter (Packaging)

Isometric View of Inverter Pole



Purpose/Objective

- Develop high energy/high power density packaging for high temperature SiC Power Electronics
- Design, fabricate and test a 300kW continuous SiC inverter with surge capability up to 1MW and operating at 300C and 100kHz carrier.

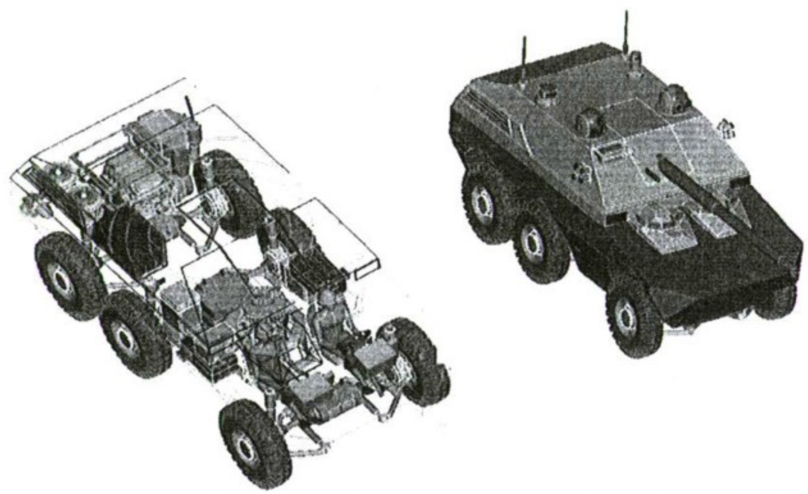
Accomplishments

- Developed conceptual mechanical design
- Completed layout and model of switch cell package; constructed working SiC mini-inverter
- Completed initial thermal model
- Identified key technology areas where improvement is needed - low defect substrates - investigating solutions

Issues

- None

Virtual Prototype



Purpose/Objective

- Develop and validate computational framework for design of hybrid electric combat vehicles
  - Total system engineering approach
  - Variable fidelity multi-process simulation and modeling tools
  - Traceable to detailed design codes and actual performance of power components

Accomplishments

- Enhanced the DARPA MatLab tool boxes to simulate CHPS hardware
  - Implemented thermal calculation
  - Integrated traction motor control scheme
  - Integration of Ni-Cd battery model
  - Interfaced detailed electrical models integrated into system

Issues

- None

Program Plans
Combat Hybrid Power System (CHPS)

Objectives for FY00 and FY01

- **Complete SIL with current state-of-the-art components**
  - demonstrate baseline performance of individual and integrated power system hardware
  - demonstrate power system management and control algorithms
  - demonstrate hardware-in-the-loop virtual prototype (VP)
- **Design and fabricate advanced components**
  - turbo-electric compounded diesel engine for prime power
  - lithium ion battery pack for energy storage
  - flywheel for pulse power
  - silicon carbide based inverter
- **Integrate advanced components into SIL and VP and validate performance benefits and utility**
- **Configure system for transition to Army**
- **Transition to Army TACOM-TARDEC**

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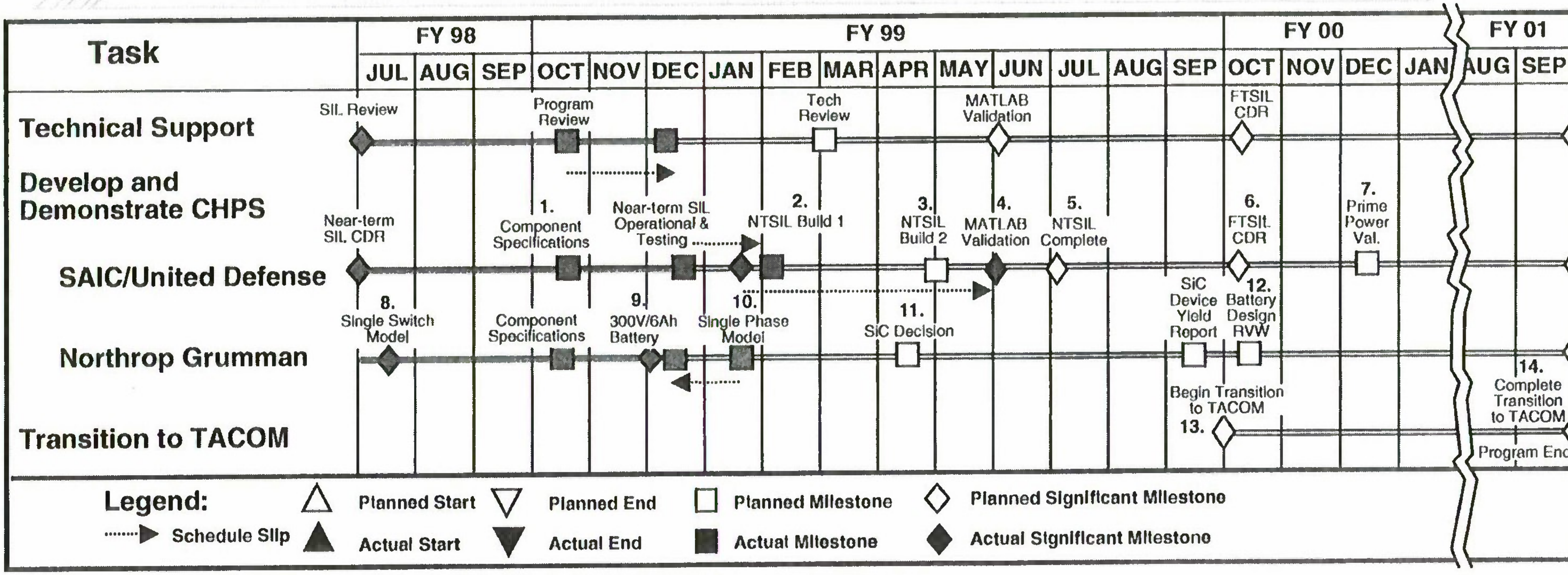
Top Level Milestone Schedule

Combat Hybrid Power Systems (CHPS)



MILESTONES AND DECISIONS MONTH/YEAR

1.	Component Specifications - Interface Control Documents (ICD's) available	10/98
2.	NTSIL Build 1 - NTSIL Build 1 operational and testing	2/99
3.	NTSIL Build 2 - NTSIL Build 2 operational and testing	5/99
4.	MATLAB Validation - validation of MATLAB and Virtual Prototype with "hardware in the loop"	6/99
5.	NTSIL Complete - demonstrate integrated operation of all components in NTSIL	7/99
6.	FTSIL CDR - Far-Term SIL Critical Design Review	10/99
7.	Prime Power Validation - performance assessment of TEC-HSDI Diesel Engine/Generator	12/99
8.	Single Switch Model - SiC device models available for testing, validation and subsystem modeling	7/98
9.	300V/6Ah Battery - first dual-mode Li-Ion battery available for testing	11/98
10.	Single Phase Model - successful demonstration of all SiC motor control micro-inverter	12/98
11.	SiC Decision - decision on SiC invertor for FTSIL Flywheel invertor	4/99
12.	Battery Design Review - dual-mode Li-Ion battery review for FTSIL	10/99
13.	Begin Transition to TACOM	10/99
14.	Complete Transition to TACOM (Based on Top Level Schedule) and Program End	9/01

CHPS "Firsts" Program Accomplishments

- **First feasibility demonstration of integrated prime power, energy storage and pulsed power using a single DC bus with load management while simultaneously supplying realistic, multiple, continuous and dynamic ground combat vehicle loads**

- **First demonstration of high power/high energy density storage systems and power conditioning components that will enable significant reduction in weight and volume for future military systems**
  - Dual-mode flywheel, compatible with military vehicles, for energy storage
  - High power/high energy (dual-mode) Li-Ion battery (1000 W/kg, 100 Wh/kg)
  - Silicon Carbide inverter to achieve high temperature and high frequency operation in active power conditioning

- **First demonstration of hybrid electric land combat vehicles' capabilities for variety of mission profiles and power management strategies using combination of validated Virtual Prototype and Systems Integration Laboratory (SIL), operating with "hardware in the loop", focused on power system and subsystem performance**

CHPS Summary & Transition Realities

CHPS will demonstrate benefits of designing combat vehicles from a power system perspective

- Verify and quantify advantages of hybrid power sharing & intelligent power management
  - Lower system weight and volume for comparable capability
  - Higher system fuel efficiency
- Advanced power components (flywheels, LI-ion batteries, SiC inverters)
- Identify and quantify potential issues - EMI, rotating machine safety, thermal management

CHPS will develop several tools for the Army to use

- SIL for experimentation with hybrid power systems and advanced power technologies
- End-to-end Virtual Prototype for designing power architectures for a wide range of combat systems

CHPS does not

- Demonstrate integration of weapon systems or survivability elements
- Address technical issues associated with weapon technologies or survivability system loads
- Demonstrate required power levels for EM armaments